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Damping response of composites beams with carbon nanotubes

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ABSTRACT

Damping response of composite beams with carbon nanotubes (CNTs) have been studied carrying out free vibration tests. Simple and sandwich beams are manufactured with aluminum, epoxy resin and different types of CNTs. For comparison purposes, sandwich and simple beams with neat epoxy resin were also made and tested. 5 wt% of CNTs is added as filler in the epoxy matrix in all cases. Damping ratio is obtained by means of logarithmic decrement and half-power bandwidth method. Short aspect ratio multiwalled non-functionalized nanotubes are found to be the most effective for improving damping properties in both types of beams.

1. Introduction

Since the discovery of carbon nanotubes (CNTs), exceptional mechanical, electrical and physical properties have been reported by several researchers [1,2]. One such promising application is CNT-based reinforced composites which are being used as structural components in aerospace and automobile industry. CNTs have been observed to drastically change the properties of polymer composites [3,4]. On the other hand, epoxy resin is a cross linked polymer widely used as a matrix for advanced composites given its good stiffness, specific strength, dimensional stability and chemical resistance. The main drawback of epoxy resins for structural applications may be its inherent brittleness which could be partially overcome by adding CNTs.

The efficiency of CNTs as reinforcement in nanocomposites depends on two critical aspects: *dispersion* of the nano reinforcement filler within the matrix and a *strong interfacial bonding* between the reinforcement element and the matrix. A good dispersion is achieved depending on the length of the CNTs, their entanglement, the volume fraction of CNTs, the viscosity of the matrix, the inter-tube attraction and the dispersion technique [5]. On the other hand, a chemical functionalization not only can improve the dispersion but also augment bonding strength at the polymer–nanotube interface [6,7]. Also the curing cycles of the composites is another influencing factor. Even when the kind of CNT is different, Guzmán et al. [8] and Montazeri et al. [9] agree that the effect of nanotube reinforcement is more pronounced for resin that was cured at lower time.

Hernandez et al. [10] studied the mechanical properties of an epoxy/CNT composite with two aspect ratio nanotubes. While tensile properties showed very limited improvement, the impact resistance and fracture toughness of the nanocomposites were significantly improved, especially for the composites employing the nanotubes with higher aspect ratio. Improvements in the glass transition temperature and storage modulus were also greater for the composites utilizing the larger tubes. Montazeri et al. [11] found that the addition of both untreated and acid treated multi-walled carbon nanotubes (MWCNT) led to a non linear increase in Young's modulus and tensile strength but the fracture strain diminished. Better dispersion and higher tensile strength values were observed with shorter nanotubes.

Concerning the amount of CNTs, small addition of single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT) can improve the mechanical properties of nanocomposites [12,13]. Guo et al. [14] found that the tensile strength and fracture toughness was improved with 8 wt% of CNT but the elastic modulus was reduced monotonically. Carbon nanotubes may also be Aligned to optimize the properties of these reinforcing systems, orienting them in the principal directions of the structures. Cheng et al. [15] fabricated nanocomposites controlling the alignment of CNTs and improved 716% and 160% the Young's modulus and the tensile strength with 16.5 wt% of CNTs. Also, the electrical conductivity was extraordinary augmented. However, Martone et al. [16] affirmed that the maximum reinforcement efficiency can be achieved at very low concentration of CNTs. And the reinforcement is related whit the development of a percolative network of nanotubes. Below the percolation threshold the CNT contribute

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Table 1
Carbon nanotubes properties.

CNTs	Internal diameter (nm)	External diameter (nm)	Length (μm)	SSA (m^2/g)	Making method	Functional group
SM5	5–10	20–30	0.5–2	>110	CVD	–
MC7	5–12	30–50	10–20	>60	CVD	0.73 wt% Carboxyl (COOH)
MH7	5–12	30–50	10–20	>60	CVD	1.06 wt% Hydroxyl (OH)
Aligned	2–7	10–20	5–15	40–300	CVD	–

to the composite modulus whereas it dramatically decrease above this limit. The above references demonstrate that there is no agreement between the various authors that study nanocomposites regarding its composed mechanical properties. Therefore, at present, this is a topic of study, research and discussion.

In the last years, damping capacity of materials had been a topic of interest because of their structural application. Nanocomposites containing carbon nanotubes can achieve high damping capacity by taking advantage of the weak bonding and interfacial friction between individual nanotubes and the matrix. Kireitseu et al. [17] reported a 200% increase in structural damping and 30% increase in stiffness due to 2% of nanotube reinforcement. Rajoria and Jalili [18] found that storage modulus of epoxy is not significantly affected by addition of CNTs, while the loss modulus can be altered. MWCNTs were found to be better reinforcement choice for damping enhancement. Up to 700% increase in damping ratio was observed by using 5.0 wt% MWCNTs in epoxy as compared to plain epoxy. A maximum in damping ratio at about 5.0 wt% was observed for both MWCNT and SWCNT reinforcements. Yeh and Hsieh [19] investigated the dynamic properties of sandwich beams with MWCNT/polymer nanocomposites as core materials. The face laminate dominated the stiffness of the sandwich beams and the natural frequencies of sandwich beams were affected directly by the face materials and decrease with increasing fiber orientations of the graphite/epoxy face laminates. Increasing the thickness of the cores increased both the natural frequencies and the loss factors of the sandwich beams. The core materials dominated the damping characteristics of the sandwich structure. Khan et al. [20] studied nanocomposites and carbon fiber reinforced polymer composites containing CNTs and found that damping ratio is enhanced with the addition and amount of CNTs. Tahan Latibari et al. [21] modeled a representative volume element (RVE) nanocomposite for studying damping characteristics. They showed that beyond the point where the RVE has the highest loss factor, the loss factor decreases so the influence of CNTs in damping characteristics decreases. Kiral et al. [22] studied the free vibration response and damping characteristic of a composite beam having a single impact failure on it. They showed that the damping ratio is more sensitive to a failure than the natural frequency. de Borbón and Ambrosini [23] presented an experimental study of the dynamic response of composite aluminum epoxy resin–CNT sandwich plates subjected to blast loading. It was observed that, once the composite material with CNTs has reached the fracture, it is exhibited better energy dissipation behavior than the neat epoxy specimens.

In this work, the damping characteristics of sandwich and simple composite beams are studied. Different types of MWCNTs are used as filler in an epoxy matrix. Damping ratio is obtained by means of logarithmic decrement and half-power bandwidth method. The most efficient types of MWCNT in order to increase damping were determined.

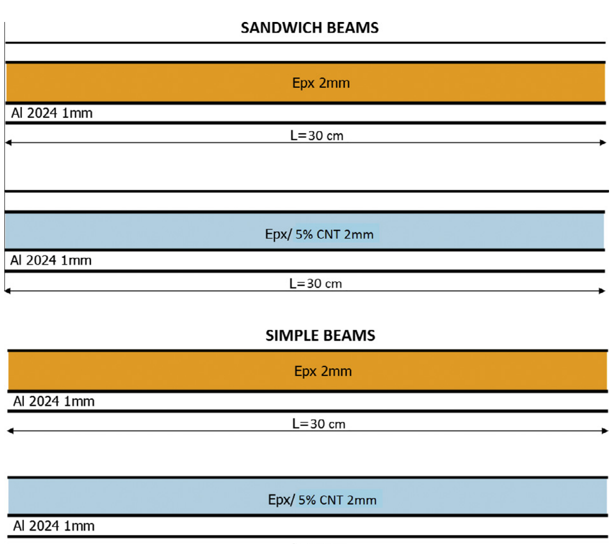

Fig. 1. Scheme of specimens for free vibrations test.

2. Materials and methods

2.1. Materials

Different types of MWCNTs were obtained from Chengdu Organic Chemicals and Co. (www.timesnano.com, made in China) and MWCNT Aligned CNTs were obtained from Nanostructured and Amorphous Materials Inc. (www.nanoamor.com, made in USA). The nanotubes were used as fillers in the epoxy matrix and their properties are presented on Table 1. According with their manufacturers; the nanotubes had purity over the 95%. The nanotubes were utilized as received from the manufacturer. The epoxy matrix was formed by Epokukdo YD-128 epoxy resin and the curing agent was an aromatic amine modified Docure TH-430 (www.kukdo.com, made in Korea). The correct volume ratio was 60 parts of hardener by 100 parts of resin. The aluminum plate was Al 2040–T3 (www.aloca.com, made in USA) which is characterized by its stiffness, fatigue performance and good strength. The plate thickness of aluminum Al 2040–T3 was 1 mm.

2.2. Preparation of composites beams and neat resin specimens

First, aluminum plates of 320 mm × 15 mm were cut. The plates were sand blasted to improve the adherence with the epoxy and put into molds. Nanocomposites were prepared using 5 wt% of SM5, MC7, MH7 and Aligned CNTs as filler in the epoxy matrix. The epoxy resin was heated at 70 °C to prevent bubbles. Carbon nanotubes were added and mixed manually at macroscopic level for 10 min. For some samples, a magnetic stirrer was used to mix the parts but the obtained results were similar to manual mixing. After that, the curing agent was added to the epoxy/CNT and mixed for 10 min at 70 °C. The mixing ratio was one part of epoxy by 0.6 parts of curing agent.

Two types of composites beams were made (Fig. 1). The first one is a sandwich beam with epoxy/CNT core and the second one has a one side aluminum beam and it is called simple beam. In simple beams, the mixture was cast into the molds and cured at room temperature. In sandwich beams, a portion of the mixture was cast into the molds and cured for 5 h at room temperature. Then, the remaining mixture was added until achieve the thickness

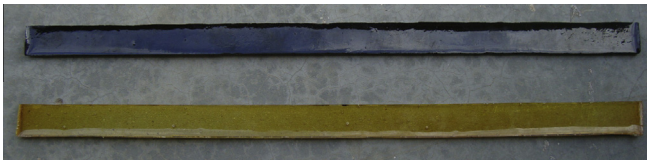

Fig. 2. Simple beams of epoxy and epoxy/CNT.

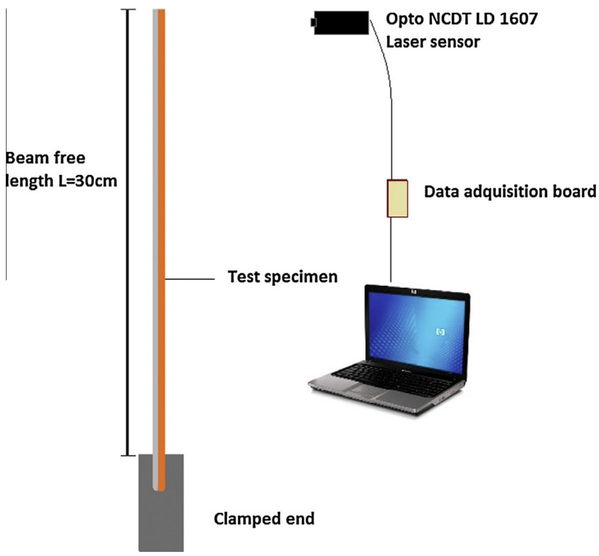

Fig. 3. Scheme of the experimental set up.

wanted and cured at room temperature. In these conditions the maximum strength is reached to 7 days. For comparison purposes, neat epoxy composites were made with the same procedure.

For both type of beams (sandwich or simple), three specimens of each type of composite matrix were made reaching 30 specimens to be tested. Samples of the simple beams once cured are shown in Fig. 2.

3. Experimental procedure

A laser sensor Micro Epsilon opto NCDT LD1607 was used to measure the dynamic response of the beams. A data acquisition board Computer boards PCM-DAS16D/16 of 16 bit of resolution and a maximum conversion time of 10 ms (100 kHz) was mounted on a notebook computer in order to record and process the signal by means of the program HP VEE 5.0 [24]. One channel was used in all tests.

The signal was sampled with the following parameters: $N = 10{,}000$ (total number of points), $n = 1000$ (sampling rate or number of points per second), $T = 5$ s (total time of the sample). An algorithm to obtain and process the data was programmed. After applying the Fast Fourier Transform, the Fourier spectrum was obtained.

The composite beams were tested as cantilever beams. An initial tip displacement was given and then released, recording the time history of displacements. A scheme of the experimental set up of the test is shown in Fig. 3.

4. Testing and results

From the tests, it was observed that the first mode was dominant. The influence of CNTs in damping can be simply observed from the displacement records (Fig. 4) for both types of beam being more prominent, as expected, on simple beams.

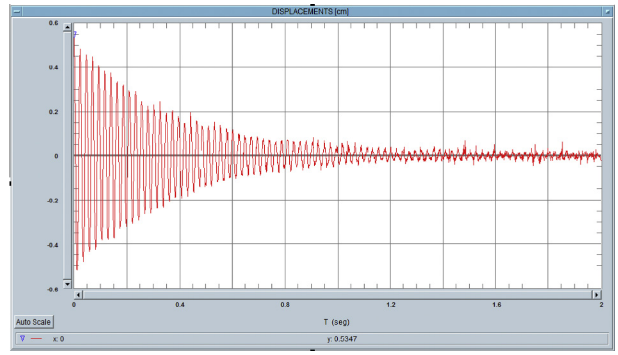

Fig. 4a. Sandwich epoxy beam.

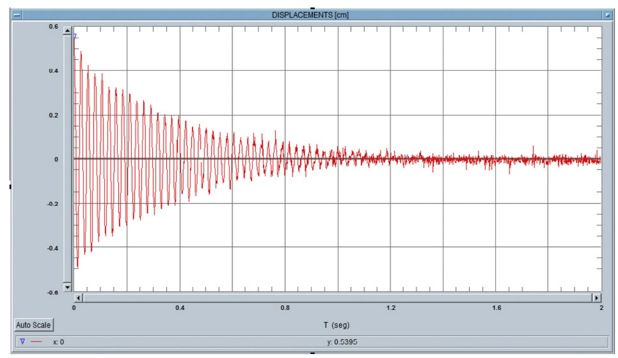

Fig. 4b. Sandwich epoxy/SM5 MWCNT beam.

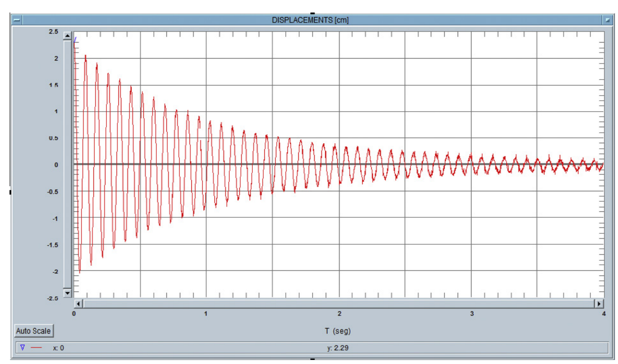

Fig. 4c. Simple epoxy beam.

The initial vibration amplitudes were selected so that they were the same for all beams. The vibration data were processed to determine the damping ratio ξ. The damping ratio of composite beams was found using logarithmic decrement method:

$$\xi_1 = \frac{\delta\sqrt{1-\xi_1^2}}{2m\pi} \tag{1}$$

where δ is the logarithmic decrement of two cycles separated m times.

Also, the damping ratio of composite beams was calculated based on the half-power bandwidth method according to the following equation:

$$\xi_2 = \frac{\Delta\omega}{2\omega_n} \tag{2}$$

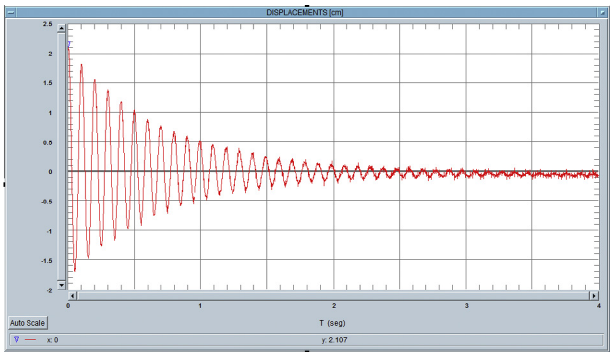

Fig. 4d. Simple epoxy/SM5 MWCNT beam.

Table 2
Damping ratio of sandwich beams.

Core material	ξ_1 (%)	ξ_2 (%)	ξ (%)
Epoxy	0.90	0.94	0.92
Epoxy/SM5	1.20	1.28	1.24
Epoxy/MC7	0.53	0.50	0.52
Epoxy/MH7	0.98	1.01	1.00
Epoxy/Aligned	1.23	1.22	1.23

where $\Delta\omega$ is the difference between frequencies ω_1 and ω_2 corresponding to half power points around the fundamental frequency ω_n. Results of these methods are presented on Tables 2 and 3 where ξ is the average value between ξ_1 and ξ_2. Moreover, each individual value on Tables 2 and 3 is an average of the results of the three specimens tested for each case.

The influence of the type of nanotube in damping ratio is investigated for sandwich and simple beams which results are presented in Figs. 5 and 6.

It can be seen that both sandwich and simple beams with epoxy/CNT SM5 have the highest damping ratio. In the case of sandwich beams, 5 wt% of CNT in the epoxy matrix, led to an improvement of 35% compared to sandwich beams with neat epoxy core. The simple beams had an excellent improvement of 73% related to simple beams with neat epoxy. According with the "stick–slip" mechanism [18], a damping enhancement occur when the adhesion between the nanotube (filler) and the epoxy (matrix) is poor. The nanotubes elongate with the epoxy and remain bonded until a critical value, but once the external load exceeds this critical value, the epoxy starts flowing over the surface of nanotube in the slipping phase. In the case of SM5 nanotubes, the slippage is also induced by the CNT multi layers.

It should be mentioned that the stiffness of the composite beams depends on the cross section of the beam and it is dominated for the stiffness of the aluminum. Adding CNTs to the epoxy will not change the general stiffness of the beams and it is not investigated in this work. However, from a point of view of the materials, the damping depends on the interfacial bonding between the nanotubes and the epoxy, and between the composite matrix and the aluminum. Assuming that the composite matrix and the aluminum are perfectly bonded, the change on damping should only be a result of adding CNTs as filler to the matrix. On the other hand, from a mechanical point of view, the core in sandwich beams is designed to resist shear stresses and the composite matrix in simple beams is designed to resist both normal and shear stresses. Therefore, the mechanism in which the load is transferred to nanotubes is different for both types of beams. Nevertheless, adding SM5 CNT into the epoxy led to an improvement of damping in both cases.

Table 3
Damping ratio of simple beams.

Core material	ξ_1 (%)	ξ_2 (%)	ξ (%)
Epoxy	1.10	1.04	1.07
Epoxy/SM5	1.90	1.81	1.85
Epoxy/MC7	1.37	1.33	1.35
Epoxy/MH7	1.52	1.58	1.50
Epoxy/Aligned	1.37	1.29	1.33

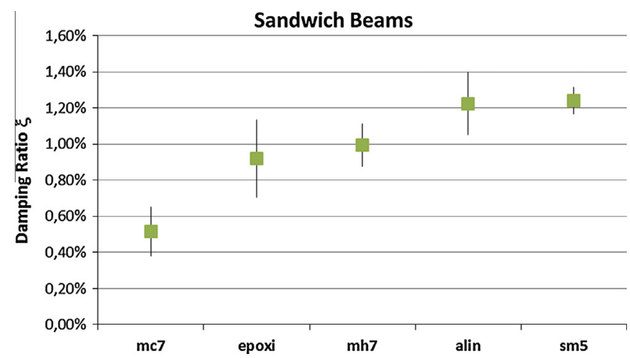

Fig. 5. Damping ratio of sandwich beams depending on the type of CNT.

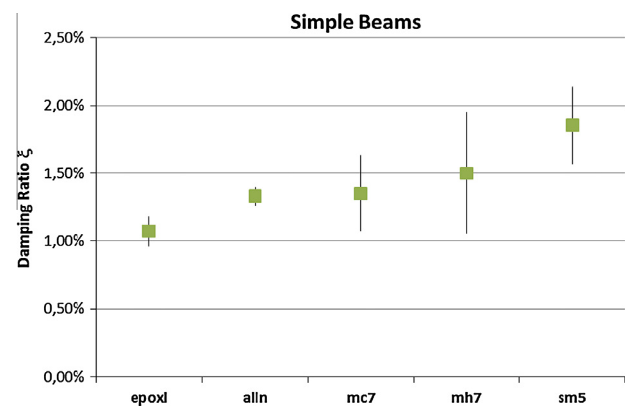

Fig. 6. Damping ratio of simple beams depending on the type of CNT.

In sandwich beams, adding CNTs Aligned into the core had also a good performance enhancing damping ratio. Even it is comparable to epoxy/CNT SM5 beams. However, in simple beams, the epoxy/CNT Aligned beams had a similar behavior than beams with epoxy/CNT MH7 (OH–CNT) and epoxy/CNT MC7 (COOH–CNT). Finally, functionalized nanotubes had not an outstanding performance improving the damping ratio. However, hydroxyl functional group is better than carboxyl functional group in order to improve the damping properties of the beams.

5. Conclusions

Free vibration test of composite beams with various types of MWCNTs were performed in order to study its damping response. The influence of four different types of MWCNTs added as filler in an epoxy matrix is studied. For comparison purposes sample with neat epoxy resin were also built and tested. Two types of beams were studied: sandwich and single beams, in which the matrix has different mechanical behavior.

It was found that 5 wt% of SM5 CNTs in the epoxy matrix led to an improvement on damping ratio of 35% for sandwich beams and 73% for simple beams compared to beams with neat epoxy. This type of multiwalled nanotube has a short aspect ratio and it is no functionalized. This benefits the stick–slip mechanism. Adding Aligned nanotubes also significantly improved damping in sandwich beams. It is important to note that, both SM5 and Aligned nanotubes, have a higher specific surface area (Table 1) and are not functionalized. Consequently, functionalized nanotubes are not recommended to improve damping properties. Regarding the higher specific surface area; it is suggesting that there are more surface to dissipate energy by friction.

It is very interesting to note that similar results for MWCNTs with a lower aspect ratio were obtained by Saw et al. [25] in connection with enhanced electrical conductivity in flexible films made from multiwalled carbon nanotube/epoxy composites.

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