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A Review of Vibration Analysis of CNT Reinforced Polymer Composites

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Abstract In this review paper, the dynamic characterization and structural optimization of a carbon nanotube reinforced laminated hybrid composite plate are surveyed. The governing differential equations of motion of a carbon nanotube (CNT) reinforced hybrid composite plate based on higher-order shear deformation theory is reviewed in finite element formulation. The stiffness and damping properties of the composite plate are significantly varied depending upon the percentage of CNT reinforcement and aspect ratio of CNT. The validity of the developed formulation is demonstrated by comparing the natural frequencies evaluated using present FEM with those of experimental work and available literature. Various parametric studies are also performed to investigate the effect of aspect ratio and percentage of CNT content and ply orientation and boundary conditions on carbon nanotube and mode shapes of a carbon nanotube-reinforced composite plate. The optimal ply configuration, aspect ratio and volume fraction of CNT can be identified by formulating the multi-objective optimization problem to yield the maximum stiffness and modal damping factors. The significance of CNT reinforcement and simulated results may serve as guidelines in designing laminated hybrid composite plate structures used in aerospace. This study will provide a useful reference to the design and fabrication of fiber-reinforced plastics for many instruments such as automotive components, golf shaft for sports, bicycle helmet for sports, the body of the sailing vessel, wind turbines, spacecraft, space elevators, solar panels and so on.

Keywords: *Carbon Nanotube, mode shapes, glass fiber reinforced Plastics*

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1. Carbon Nanotube Reinforced Polymer Composite

Glass Fiber Reinforced Plastics (GFRPs) are novel composite materials which consist of glass fibers and a polymer matrix. The glass fibers are usually stacked in many orientations to obtain the desired properties. Thermosetting polymer like epoxy and polyester resins is often used as the matrix for GFRP. Many of literatures [1-6] GFRPs are widely used in aerospace and automotive industry owing to their lightweight, high specific strength and excellent impact resistance. Because of those numerous advantages, GFRPs are used in sports instruments, such as golf shaft for sports, bicycle helmet for sports, the body of sailing vessel and so on [7]. The brittle nature of the polymermatrix; however, may reduce the performance of GFRPs. It is important to further improve the properties of GFRPs to widen its applications [8]. The integration of a Nano constituent into polymer composite allows the properties to be customized and optimized. A widely used Nano constituent is the carbon nanotube (CNT), as it possesses excellent mechanical, thermal and electrical properties. As a result, CNT is employed as reinforcement to several polymers, such as epoxy, and alumina composites [8]. Numerous studies [9,10] have shown that a good dispersion of nanotubes enhances the physical properties of the composites. However, it is difficult to disperse CNTs well in the resin. As a result, different dispersion methods need to be explored. CNTs can exist as one graphene layer, known as single-walled CNT (SWCNTs), or exist as many graphene layers, known as multi-walled CNT (MWCNTs). Although the reported properties of CNTs, such as the modulus and strength, varied in literatures [11,12], the general trend showed that CNTs had superior mechanical properties than many other engineering material. As such, CNT is an ideal candidate as reinforcement in nanocomposites. Kimet al. [13] discussed that the addition of MWCNTs to plain-weave glass/epoxy composites had little effect on the tensile properties, which were dominated by the fiber properties. However, the MWCNTs affected the related interlaminar fracture properties, which were dominated by the matrix properties, because the MWCNTs strengthened the matrix rich regions and therefore the interface between the glass fibers. They also discovered the optimum tensile stiffness and strength when the MWCNT content was 0.4%. The extremely high modulus and tunable electrical and thermal properties of carbon nanotubes offer an appealing mechanism to dramatically improve both strength and stiffness characteristics, as well as add multifunctionality to polymer based composite systems. Much of the discrepancy in the published results can be attributed to nonuniformity of material samples: in order to obtain optimal property enhancement, key issues to be resolved include improved dispersion of nanotubes, alignment of nanotubes, functionalization of the nanotubes to enhance matrix bonding/load transfer, and efficient use of the different types of nanotube reinforcements single wall versus nanorope versus multiwall. Ongoing investigations are focusing on improved processing and design of Nano composites with emphasis on controlled nanotube geometric arrangement. Techniques to get homogeneous dispersion and significant alignment of the nanotubes include application of electrical field during polymerization, extrusion and deformation methods. In addition to dispersion and alignment, recent work has demonstrated that the waviness of the nanotubes in the polymer decreases the potential reinforcing factor by an additional 50% beyond a two-fold decrease due to random orientation. Andrews et al [14] experimented for a MWCNT reinforced polymer and where good dispersion and matrix bonding was achieved. In this case, using only 0.5 capacity unit nanotube reinforcement with no alignment and moderate NT waviness, elastic stiffness was improved 40% over that of the neat matrix material and strength values improved nearly 25% in polymers with a micron sized reinforcing phase.

2. Carbon Nanotube Structure

Since its discovery in 1991 by Iijima while experimenting on fullerene and looking into soot residues, two types of nanotubes have been made, which are single walled carbon nanotubes (SWCNTs) and multi walled carbon nanotubes (MWCNTs). SWCNT consists only of a single graphene sheet with one atomic layer in thickness, while MWCNT is formed from two to several tens of graphene sheets arranged concentrically into tube structures (Figure 2). The SWCNTs have three basic geometries, armchair, zigzag and chiral forms as presented in Figure 1.

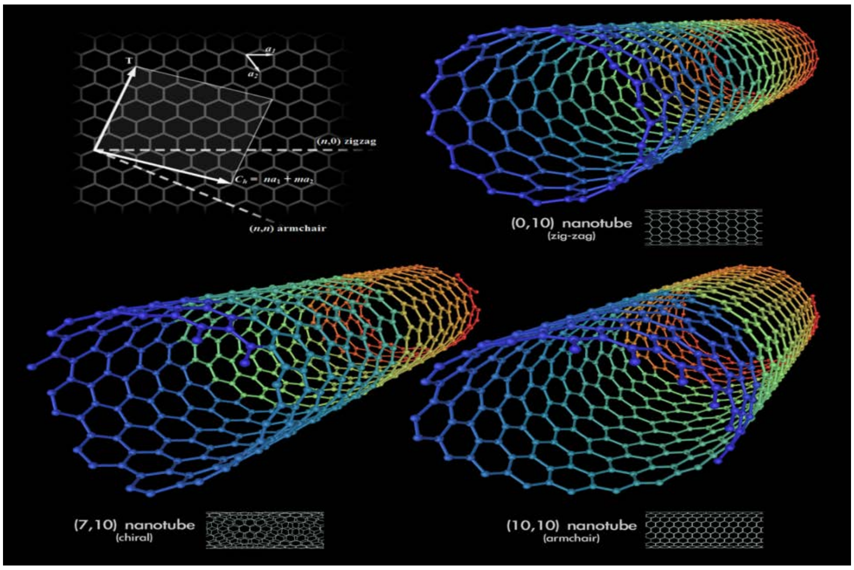

Figure 1. Single wall Carbon Nanotube

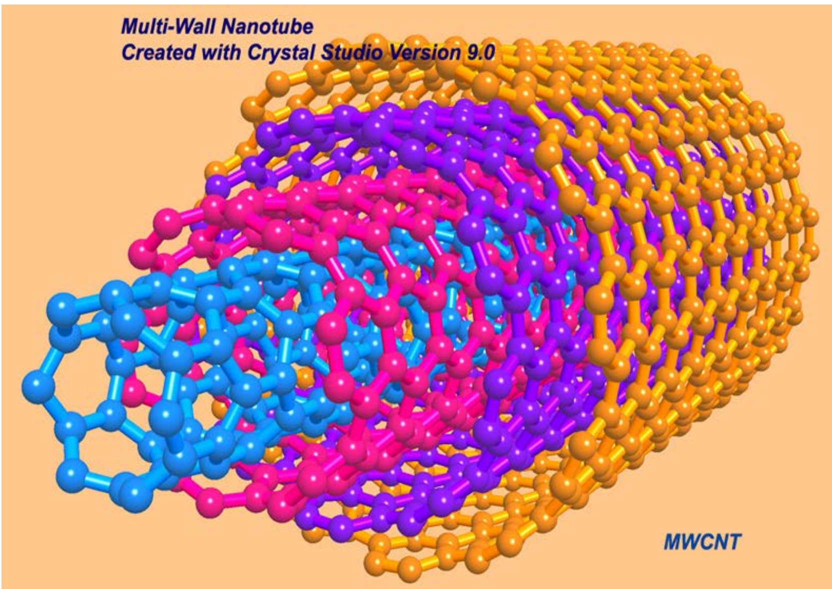

Figure 2. Multi wall Carbon Nanotube

3. Theoretical and Vibration Analysis of CNT Reinforced Polymer Composites

Dickeya and Qian [15] have conducted an experiment on multiwall carbon nanotubes dispersed homogeneously throughout polystyrene matrices by a simple solution-evaporation method without destroying the integrity of the nanotubes. Tensile tests on composite films show that 1 wt% nanotube additions end in 36%–42% and 25% increases in coefficient of elasticity and break stress respectively, indicating significant load transfer across the nanotube-matrix interface. DeValve and Pitchumani [16] have conducted an investigation of the damping effects of carbon nanotubes (CNTs) embedded in the matrix of fiber-reinforced composite materials. Several different aspect ratios, types, and weight fractions of CNTs are considered, and an analysis of the CNT dispersion within the composite matrix is presented. The composite materials are analyzed using dynamic mechanical analysis and various modal analysis techniques to work out the damping characteristics of the composite as a function of strain, fiber volume fraction, and nanotube type and weight percentage loading. Experiments are conducted using cantilevered beams in both a stationary and rotating frame in order to explore the effects of rotation on the damping behavior of the composite material. The results show that the addition of 2% weight of CNTs to the matrix of carbon fiber reinforced composites can increase the damping in a stationary composite beam by more than 130% and by more than 150% in a composite beam rotating at 500 RPM. Frank and Ko [17] have suggested the composites that consist of materials in fiber form suspended in a matrix material are stronger than bulk materials of the same type due to the reduced chance that flaws will be included. In fact, the states as the diameter of matter get even smaller as in the case of nanotubes, the strain rate of energy per atom increases exponentially, contributing to the enormous strength of over 30 GPa for carbon nanotubes. It is important to note, however, that the strength of a CNT reinforced composite can be seriously impacted by the aspect ratio of the nanotube as well as the type of interface between the CNT and the polymer matrix. Yang et al. [18] have reported regarding the SWCNTs are modeled as nanobeams where the consequences of transverse shear deformation and rotary inertia are considered within the framework of Timoshenko beam theory. The governing equations and boundary conditions are derived by using Hamilton's principle. The differential quadrature (DQ) method is employed to discretize the nonlinear governing equations which are then solved by a direct iterative method to obtain the nonlinear vibration frequencies of SWCNTs with different boundary conditions. Mahmoud and Amal [19] have evaluated the technical and economic feasibility of using carbon nanotubes in reinforcing polymer composites. They were concluded carbon nanotubes can be used in conjunction with carbon fibers in a hybrid composite in order to achieve elastic modulus values in the range 170-450 GPa. As the sole reinforcing phase, carbon nanotubes present a viable option if coefficient of elasticity values on the order of 600 GPa are desired. These conclusions are confirmed by a case study to pick the optimum material for a tennis racquet using the analytic hierarchy process.

Ping et al. [20] have investigated the bending and free vibration analyses of thin-to-moderately thick composite plates reinforced by single-walled carbon nanotubes using the finite element method based on the first-order shear deformation plate theory. Four sorts of distributions of the uniaxially aligned reinforcement material are considered, that is, uniform and three sorts of functionally graded distributions of carbon nanotubes along the thickness direction of plates. The effective material properties of the nanocomposites plates are estimated according to the rule of mixture. Detailed parametric studies are administered to reveal the influences of the quantity fractions of carbon nanotubes and therefore the edge-to-thickness ratios on the bending responses, natural frequencies and mode shapes of the plates. In addition, the consequences of various boundary conditions also are examined. Numerical examples are computed by an in-house finite element code and therefore the results show good agreement with the solutions obtained by the FE commercial package ANSYS. Ronald et al. [21] have explored the major difficulties encountered during processing of carbon nanotube-reinforced or nanoparticle reinforced polymer composites is the inability to achieve a uniform dispersion of the nanotubes or nanoparticles in the liquid polymer. Nanotubes tend to cluster due to physical entanglements of the tubes, Vander walls forces between the carbon surfaces, and the fact that the surface energy of the nanotube clusters is thought to be less than that of the corresponding collection of individual nanotubes. Various methods of achieving uniform dispersion of nanotubes in liquids have been reviewed by past research papers, and one of the most widely used methods is sonication. Gopalakrishnan et al. [22] have investigated the spectral finite element formulation for uniform and tapered rotating CNT embedded polymer composite beams. The exact solution to the governing differential equation of a rotating Euler–Bernoulli beam with maximum centrifugal force is used as an interpolating function for the spectral element formulation. Free vibration and wave propagation analysis are carried out using the formulated spectral element. In this paper, they have explained the substantial effect of volume fraction and L/D ratio of CNTs in a beam on the natural frequency, impulse response and wave propagation characteristics of the rotating beam. It is found that the CNTs embedded within the matrix can make the rotating beam non-dispersive in nature at higher rotation speeds. Embedded CNTs can significantly alter the dynamics of polymer-nano composite beams. The results also are compared with those obtained for carbon fiber reinforced laminated composite rotating beams. It is observed that CNT reinforced rotating beams are superior in performance compared to laminated composite rotating beams. Sreejarani et al. [23] explored the synthesis and processing of CNT-reinforced epoxy composites. The modification of epoxy resins with CNTs could endow the materials with some superior properties such as significant increases in mechanical properties and substantial improvement in thermal and electrical conductivity. The reports published so far on these materials focus on investigating whether a CNT-modified epoxy matrix yields improved properties with neat epoxy as the matrix material. Various types of CNTs with or without physical and chemical modifications were utilized to fabricate the composites to make them effective fillers regarding mechanical properties, especially toughness and the properties of the resulting composites were also analyzed. However, the extent of homogeneous dispersion is found to be dependent on the aspect ratio, volume fraction, CNT entanglement, matrix viscosity, and inter-tubular interactions. Different methods including sonication, stirring and calendaring have been proposed for the preparation of composites where some of the reports contradict each other in the effectiveness to get uniform CNT distribution. Though the CNT-reinforced epoxy has been shown to be a possibility, realizing the properties of individual CNTs in assemblies of CNTs is a formidable challenge.

Yildirim et al. [24] have explored the effects of pressure on intertube distance and found that under certain conditions, the nanotubes underwent a structural phase transformation from the traditional Vander walls lattice to a new lattice where the nanotubes were covalently bonded in the area where the strain was the largest. Increasing the pressure revealed that different interlink lattices could be created, allowing optimization of the desired characteristics for the fibers based on the desired application. Alignment also plays an important role in the strength of a CNT reinforced composite.

Thostenson and Chou [25] presented the importance of alignment of CNT in a polymer. It was shown experimentally the elastic modulus of the uniformly aligned CNT could be enhanced almost five times as that of the randomly oriented composite.

Wan and Delale [26] have investigated the finite element analysis of single-wall carbon nanotube embedded in a polymer matrix. They examined the change in strain energy per unit length for three interface types and several aspect ratios under two types of loading conditions. The results of this analysis show that beyond a certain aspect ratio, the change in strain energy per unit length began to converge to a certain value. From this, we can conclude that if we ensure that a CNT reinforced composite contains nanotubes in the steady region (above an aspect ratio of 310), effective load transferral will occur.

Wanga et al. [27] have developed the SWCNT Timoshenko beam models for the free vibration of CNTs with various end conditions. The models allow for the effects of transverse shear deformation and rotary inertia. For an SWCNT Timoshenko beam model, it is found that the above-mentioned effects lead to a decrease in frequencies when compared to those obtained by the Euler beam model. This phenomenon is expanded at higher mode numbers and for small length-to-diameter ratios. With increasing length-to-diameter ratios, the effects of shear deformation and rotary inertia on the frequencies diminish and the results given by the Timoshenko beam model are equivalent to those of the Euler beam model.

Ambrosini and Borbon [28] presented the damping response of polymer resin-based composite beams with CNTs. The damping properties of CNT reinforced resin-based composite structures have been studied by many investigators. The natural frequencies of a composite beam without and with CNT reinforcement are also compared. It is shown that the addition of CNT in fiber-reinforced polymer composite beam increases the natural frequencies significantly. It is also shown that the increase in the aspect ratio of CNT in composite beams increases the natural frequencies significantly. However, no attempt has been made to study the effect of CNT reinforcement on the dynamic properties of fiber-reinforced polymer (FRP) composite bending plates.

4. Conclusions and Future Recommendations

This study may provide knowledge and information in the Nano composite material fabrication and testing research results in obtaining a low cost material fabrication for aircraft and automotive industries.

- The stiffness and damping properties of the composite plate is significantly varied depending upon the percentage of CNT reinforcement and aspect ratio of CNT.
- Furthermore, the stacking sequence and the ply orientation play a major role on the stiffness and damping properties of the structure.
- Hence, the effect of the stacking sequence and the ply orientation on the stiffness and damping properties of composite plate is investigated.
- The optimal ply configuration can be identified by formulating the optimization problem to yield the maximum stiffness and modal damping factors.
- The significance of CNT reinforcement and simulated results may serve as guidelines in designing laminated hybrid composite plate structures used in aerospace.

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