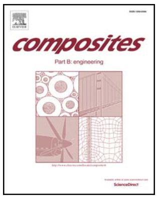
Composites Part B 141 (2018) 100–122

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb



Viscoelastic modelling and dynamic characteristics of CNTs-CFRP-2DWF composite shell structures

Ashirbad Swain, Tarapada Roy*

Department of Mechanical Engineering, National Institute of Technology Rourkela, Odisha 769008, India

ARTICLE INFO

Keywords:
CNTs
Nanocomposite
Woven fabric composites
Viscoelasticity
Mori-Tanaka method
Strength of materials method
Representative unit cell
Shell finite element
Modal loss factors
Impulse and frequency responses

ABSTRACT

The carbon nanotubes (CNTs) are well known for its application in the areas of advanced composite materials for their improved elastic properties. The large specific interfacial surface area owing to tiny dimensions of CNTs may greatly escalation the interfacial sliding which may promote the dissipation of energy in a dynamic situation that makes them very ideal for damping applications in engineering structures/systems. The present article investigates the viscoelastic modelling and dynamic responses of the CNTs – based carbon fiber reinforced two dimensional woven fabrics (CNTs-CFRP-2DWF) composite spherical shell panels where CNTs are reinforced in the polymer matrix phase. The Mori – Tanaka (MT) micromechanics in conjunction with weak interface (WI) theory has been developed for the mathematical formulations of the viscoelastic modelling of CNTs-based polymer matrix phase. Further, strength of material (SOM) method has been employed to formulate viscoelastic material behavior of the yarn and finally the viscoelastic properties of the representative unit cell (RUC) is established based on the unit cell method (UCM). An eight-node shell element with five degree of freedom per node has been formulated to study the vibration damping characteristics of spherical shell structures made by CNTs-CFRP-2DWF composite materials. The shell finite element formulation is based on the transverse shear effect as per the Mindlin's hypothesis, and stress resultant-type Koiter's shell theory. Frequency and temperature dependent material properties of such CNTs-CFRP-2DWF composite materials have been obtained and analysed. Impulse and frequency responses of such structures have been performed to study the effects of various important parameters such as volume fraction of CNTs, interfacial condition, agglomeration, temperature, geometries of shell panel on the material properties and such dynamic responses. Obtained results demonstrate that quick vibration mitigation may be possible using such CNTs-CFRP-2DWF composite material which is desirable to overcome the drawbacks of conventional CFRP woven fabric composite materials.

1. Introduction

Since several decades, woven fabric composites have gained its applications in the various field of engineering. The woven composites are well known for providing balanced properties in longitudinal and transverse direction, it can resist impact load, and also ease of handling during their manufacturing. Hence, from several decades woven fabric composites have been an important area of research. Several studies have been conducted to evaluate the elastic properties of woven composites [1–15] but few literature addressed the effects of weave geometry and constituents to the dynamic responses of material/structure [16–25].

Tita et al. [16] investigated the vibration damping behavior of woven composite beam with the help of Kennedy and Pancus [17] method that rely on the utilization of natural frequency and mode shape data from experiment. Houshyar et al. [18] also investigated different woven geometry on the viscoelastic properties of woven composites where they concluded that the dynamic mechanical properties are strongly influenced by the woven geometry of the composites. The authors also concluded that the plane weave composite shown four times higher storage modulus than stain weave composites. Kim [19] employed the technique developed by Sottos [13] to evaluate the viscoelastic storage and loss moduli of FR–4 materials used in microelectronic devices. Apart from the storage and loss moduli, the model was capable enough to predict relaxation behavior of the material system. Xu et al. [20] investigated the vibration responses of woven fabric composites where this studied concentrated on the five type of plane weaving pattern that included plane weaved pattern for their vibration damping performance. Authors concluded that the modal frequency and loss factor are more sensitive to temperature than that of material's storage and loss factor. Authors also concluded that the composites with plane weaving pattern provided higher damping. Upadhyay [21]

---

* Corresponding author.
E-mail address: tarapada@nitrkl.ac.in (T. Roy).

https://doi.org/10.1016/j.compositesb.2017.12.033
Received 24 July 2017; Received in revised form 8 November 2017; Accepted 17 December 2017

Nomenclature

k	*CNT, P, NC, F, NCF* phases
σ^k	Stress of *kth* phase
ε^k	Strain of *kth* phase
$\dot{\varepsilon}^k$	Strain rate of *kth* phase
C^k	Stiffness of *kth* phase
S^k	Compliance of *kth* phase
t	Time
ω	Excitation frequency
v_j^k	Volume fraction of *k*th phase with respect to *j*th phase
A^{dil}	Dilute strain concentration tensor
S	Eshelby tensor
$\overline{S}$	Modified Eshelby tensor
$\overline{A}^{\mathrm{dil}}$	Dilute strain concentration tensor
$\overline{A}^{\mathrm{dil}}\overline{\overline{A}}^{\mathrm{dil}}$	Modified dilute strain concentration tensor
I	Identity tensor
H	Interfacial compliance tensor
η,αandβ	Interfacial compliances
$\langle l \rangle$	Parameter l averaged over the volume
V_j^k	Volume of *k*th phase with respect to *j*th phase
$\xi\zeta$	Aggregation/agglomeration parameter
$[\bullet]^k\vert_{out}$	Parameter ([•]) related to kth phase outside inclusion
$[\bullet]^k\vert_{in}$	Parameter ([•]) related to kth phase inside inclusion
Δu_i	i^{th} component of displacement jump
$[\bullet]'$	storage parameter corresponding to [•]
$[\bullet]'^{\prime}$	Loss parameter corresponding to [•]
T	Temperature
w, f	Warp and fill
$S_{Fk}t_k$	Yarn width ($k = w, f$)
t_k	Yarn thickness ($k = w, f$)
r_k	Radius of curvature of cross-section of lenticular yarn ($k = w, f$)
l_{gk}	Gap between two yarns in direction k ($k = w, f$)
$(L_{gk})_{\min}$	Minimum value of the gap length for tight configuration in direction k ($k = w, f$)
β_k	Crimp angle for k yarn ($k = w, f$)
pf	Packing Factor
α_1, α_2	Curvilinear coordinate
A_1, A_2	Lame's parameters
N_i	Shape function corresponding to ith node
ε_{xx}^0, ε_{yy}^0 , γ_{xy}^0	In-plane strains of the mid-surface in cartecian coordinate
k_{xx}, k_{yy},k_{xy}	Bending strains of the mid-surface in the cartesian coordinates
$[B_b^e]$	Inplane strain - displacement matrix
$[B_s^e]$	Transverse strain - displacement matrix
T, U, W	Kinetic energy, potential energy and work done
$[M_{uu}^e]$, $[K_{uu}^e]$	Elemental Mass and Stiffness matrix
$[M]$, $[K]$	Global Mass and Stiffness matrix
λ_j	Eigenvalue corresponding to *jth* modal
ω_j	Natural frequency corresponding to *jth* mode
η_j	Loss factor corresponding to *jth* mode
X_j	Eigenvector corresponding to *jth* mode
$\overline{\sigma}^k$	Average stress in *kth* phase
$\overline{\varepsilon}^k$	Average strain in *kth* phase
pt	Represents a perturbation term
ε^*	Eigen-strain

developed a three-dimensional micromechanical model based on classical laminate theory in order to analyze the viscoelastic properties of woven cloth composite considering the viscoelastic effects of the matrix phase. Authors also evaluated the Prony series coefficients for various samples with different fiber volume fractions. From the hysteresis plots, the authors concluded that the energy dissipations due to loading in the out of plane normal and shear modes are significant than that of other possible mode of loading. Mishra and Sahu [22] investigated the dynamic responses of plane weave composite in order to study the effects of number of layups, aspect ratio, fiber orientation and stacking sequence on the modal parameter (such as natural frequencies and mode shapes). Rajesh and Pitchaimani [23] studied the effects of weaving pattern and interlocking hybridization on the dynamic responses and free vibration responses of woven composites. Authors conducted experimental modal analysis on the beam specimen in their study and found closeness in experimental and numerical results. Pei et al. [24] conducted numerical and experimental investigations to study the effects of different reinforcements on the dynamic properties of woven composites and concluded that fiber volume fraction and fiber orientation angle have significant effects on the dynamic responses. Rouf et al. [25] utilised multiscale modelling in order to evaluate the modal parameters of beam made by plane weave composites. Authors also used dynamic mechanical analyser and half power band width method in order to obtain flexural loss.

Though traditional fiber reinforced polymer (FRP) composite including woven composites have many advantages but they are vulnerable to fiber breakage, matrix cracking, fiber pull-out etc. With the discovery of CNTs in 1991 [26] and subsequent studies related to their mechanical properties demonstrated that the problems in conventional composites can be mitigated by dispersing CNTs in matrix phase. Many studies have found that elastic properties can be improved due to increase of CNT volume fraction in the polymer matrix phase but there is always a chance of clubbing of CNTs to each other when the CNTs is increased in the matrix phase that may form the clusters of CNTs which can influence the elastic property of CNTs based polymer composites. This phenomenon is termed as agglomeration of CNTs. Few important research work are presented in this paragraph. Shi et al. [27] presented the Mori-Tanaka based micromechanics formulations and first addressed the effects of agglomeration of CNTs on the elastic properties. Esteva and Spanos [28] considered the weak interface theory along with the Mori-Tanaka micromechanics to estimate the elastic property of CNTs-based nanocomposite.

There is a special case where the several clusters can attach to each other. Such cases are commonly termed as aggregated regions in the material system where the dense region surrounds a comparatively small region in which particle denseness is less than that of the surrounding region. Some of the important research work in this direction are presented here. Yang et al. [29] evaluated the effective elastic property of CNTs–based shape memory polymer matrix composite considering aggregation effects of CNTs. Pourasghar et al. [30] studied free vibration analysis of CNTs – based functionally graded nanocomposite cylindrical shell by differential quadrature method where the author mainly focused on the effects of CNTs – distribution and local aggregation of CNTs on the free vibration responses. Rao et al. [31] developed the Mori – Tanaka based improved micromechanical model to determine the effective elastic properties of short fiber reinforced composite incorporating porosity and local aggregation.

Few important literature on the modelling and assessment of the damping properties of CNTs based polymer composite materials are presented in this paragraph. Based on the micromechanical simulations by Finegan et al. [32] reported that nanocomposite with low fiber aspect ratios possess higher damping capacity. Zhou et al. [33] studied the structural damping properties of polymer matrix nanocomposites considering SWNTs to access the interfacial stick-slip interaction between the polymer matrix and the CNT. Rajoria and Jalili [34] experimentally investigated the damping and stiffness properties of CNTs-based epoxy matrix nanocomposite. Suhr and Koratkar [35] stated that energy dissipation occurs when the interfacial slip between CNT and