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Dynamic Response of FG-BNNT Reinforced Composite Plate Subjected to Low Velocity Impact Loading

Shakeena Dokiburra[1], Dr K Dileep Kumar [2]

[1]PhD Scholar, Department of ME, JNTUK, Kakinada, Andhra Pradesh, India

[1]Associate Professor, Department of ME, JNTUK, Kakinada, Andhra Pradesh, India

Abstract: In the world of emerging materials, composites play a major role due to their lightweight and high strength-to-thickness ratio. There are many classes of composites such as Metal matrix composites, Ceramic matrix composites and Polymer matrix composites based on the matrix. And short fibre composites, long-fibre composites and particulate composites based on the reinforcement. The materials used as matrix and reinforcement play a major role in defining the strength and properties of a composite. Of all the different composites available in today's life, Nanocomposite has become the centre of interest because it exhibits high strength with a small amount of reinforcement. The reinforcement in the nanocomposites can be of different types. They can be arranged in the form of nanotubes, nanoparticles, nanosheets etc. In this research, we focus on the polymer matrix nanocomposite taking reinforcement as the nanotubes. The mechanical properties of the nanocomposite are evaluated using the Halpin-Tsai micromechanical model and the analytical investigation is carried out using the new simple higher-order shear deformation theory and the contact force is calculated using the Hertz contact law and New mark's technique is used for numerical investigation. The dynamic response of the FG-reinforced nanocomposite is studied and the best nanocomposite from the two different matrices and fibres is discussed. The influence of fibre volume fraction, Fibre orientation and the Fibre arrangement on the dynamic response is also presented and discussed and the comparison of CNT and BNNT with epoxy as matrix is presented and the comparison of Epoxy and HDPE with BNNT as reinforcement is also studied.

Keywords: BNNT, CNT, New Simple HSDT, Functionally Graded and Halpin-Tsai Micromechanical Model

1. Introduction

Composites are made up of two or more elements combined to create a single material with superior qualities over the individual components. The qualities of the material determine the composite's strength and longevity. We have a wide range of materials with superior material qualities. A special family of materials known as nanotubes has excellent strength characteristics with their small size. High aspect ratio tubes are formed by rolling up atom sheets. The qualities, van der Waals forces, chirality, diameter, number of walls, length, and quality all influence the characteristics and functionality of nanotubes. Both carbon nanotubes (CNTs) and boron nitride nanotubes (BNNTs) have found widespread application as reinforcing fibres. In structure, BNNTs are comparable to carbon nanotubes, except that boron and nitrogen atoms have been substituted for the carbon atoms. Because of their high modulus of elasticity and exceptional stability, BNNTs exhibit remarkable mechanical behaviours that are similar to those of CNTs. However, there are still certain areas where BNNTs differ from CNTs, such their high-temperature stiffness against oxidation. Polymers that are reinforced with BNNTs have altered thermal characteristics in addition to their mechanical ones. Since they are biocompatible, they are employed in biomedical applications. As these nanocomposites have high strength, they have less resistance to impact. Many literatures are available on the impact analysis of the CNT with polymer matrices but only a few literatures are available on the BNNT as the synthesis of these materials is still under the study. The fig 1 shows the structure of both single walled and multi-walled CNT and BNNT.

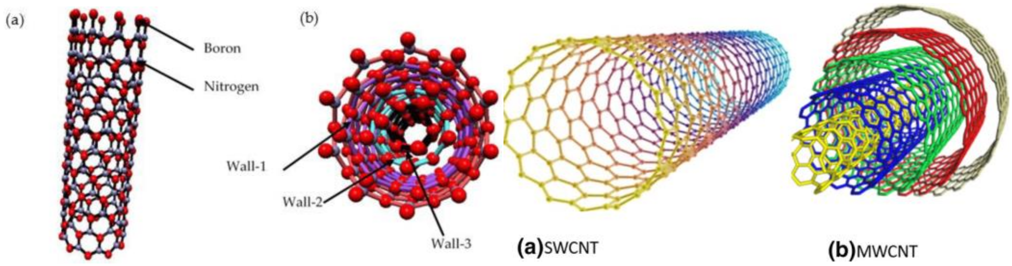


Fig 1 Structure of SWBNNT and MWBNNT and SWCNT and MWCNT

Based on molecular mechanics simulations, an analytical "stick-spiral" model of single wall boron nitride nanotubes (SWBNNTs) has been built to investigate their elastic properties [1]. Moreover, the elastic properties of BNNTs are calculated using the stress–deformation treatment of the continuous lattice thermodynamic model [2]. Furthermore, the moduli of elastic properties of double wall boron nitride nanotubes (DWBNNTs) are studied using ab-initio density functional theory [3]. Furthermore, various studies on the thermoelectromechanical preparation of BNNTs are reviewed. Based on strain gradient theory, the electro-thermal dynamic behaviour of DWBNNTs, which are mated by a visco-Pasternak medium, is investigated [4]. Furthermore, the impact of a partly filled polyethylene foam core on the treatment of torsional buckling in a polymeric cylinder reinforced by DWBNNTs is examined using the energy technique [5]. Furthermore, the nonlinear dynamic behaviours of a smart composite micro-tube reinforced by BNNTs and composed of polyvinylidene fluoride are investigated under electro thermal stress [6]. Lastly, the theories of nonlocal elasticity and piezo elasticity are applied to analyse the thermoelectric-torsional buckling response of a diamond wire braid nanotube [7].

Both static and dynamic circumstances can be used to analyse the composite structure. As far as the authors are aware, both static and dynamic analysis of the BNNT has received relatively little attention. Some of the researchers studied the dynamic behaviour of BNNTs. This dynamic response can be known when a structure is subjected to earthquakes, forced vibrations, impacts etc. Out of all the analysis performed on the structure, the impact analysis plays a crucial role in defining the structure strength and stability during collisions. This impact occurred from the external sources can vary its nature based on the velocity. The structure may be subjected to low or high velocity impact. There are many literature studies available on the dynamic response of the CNT reinforced composites, but it is in initial stage for BNNT. A 3-D atomistic analyzer based on molecular dynamics is used to simulate the dynamic behavior of cantilevered SWBNNTs in the intermediate landing scenario of the inserted mass [8]. On the basis of nonlocal piezo elasticity, the nonlinear vibration of the implanted DWBNNTs transporting viscous fluid is investigated [9]. Moreover, the piezoelectric technique and surface stress based on the Euler-Bernoulli beam are used to study the nonlocal axial and transverse oscillations of BNNT subjected to a moving nanoparticle [10]. Additionally, nonlocal piezo elasticity and Euler-Bernoulli beam theory are used to analyse the thermoelectric-nonlinear dynamic behaviour of DWBNNTs transporting viscous fluid [11]. It is discovered that temporal discretization affects nonlocal piezo elasticity in the nonlinear transverse oscillations of SWBNNT transporting viscous fluid [12]. In order to use SWBNNTs as nano sensors, the vibrational characteristics of the material are investigated with respect to point defects [13]. Finally, the dynamic response of the MWBNNT having finite lengths is studied using multiple elastic shell models [14]. Using the application of aerospace, a aero wing is analysed with three different functions using the BNNT reinforced with aluminium [15]. A low velocity impact response of the Nano fibre reinforced composite is studied using FEM [16].

The main aim of this research is to analytically investigate the dynamic response of the FG-BNNT reinforced Nanocomposite and compare it with the CNT reinforced nanocomposite to exhibit the influence of the reinforcement on the dynamic response of the plate structure when it is subjected to low velocity impact.

BNNTs have incredibly unusual characteristics, making them a promising material for many uses. The advantages of BNNTs, which are nanoscale in size and have a high aspect ratio like CNTs, include these. These are useful when it is preferable to avoid the functional features of CNTs. These materials can be employed in applications such as electronic drug delivery, nanomedicine, biomedicine, aerospace, and environmental protection because they have outstanding mechanical strength, thermal resistance, and electrical insulating qualities. The improvement of mechanical reinforcement, structural composites, thermal conductivity, high-temperature material processing, high-temperature applications (thermal barriers, fire resistance, etc.), electrical insulation, piezoelectric sensing, energy harvesting, neutron shielding, and transparency of composites can all be achieved through the use of BNNT composites.

1.1 Comparison between CNT and BNNT [3]

Table 1: Comaprision between CNT and BNNT

CNT	BNNT
Black in color	White in color
Covalent bonding	Covalent bonding with ionic components
Narrow band gap	Constant wide-band-gap
Not resistant to burning	Resistant to thermal oxidation
Elastic properties Youngs modulus is around 1 Terra paschal	Piezoelectric properties Youngs modulus is around 1-1.8 Terra pascals

2. Theoretical Formulation

To evaluate the governing equations, we are employing a new higher-order shear deformation theory which is the refined based on the HSDT with reduced unknowns. The present theory's displacement field is selected based on the following presumptions: (1) the transverse and in-plane displacements are divided into shear and bending components; (2) the in-plane displacements' bending parts resemble those provided by CPT; and (3) the shear parts of the in-plane displacements give rise to shear stresses through the plate's thickness in a manner that causes the shear stresses to vanish on the top and bottom surfaces of the plate. These presumptions allow for the extraction of the displacement field that follows.

$$U(x, y, z, t) = u(x, y, t) - z\frac{\partial w_b}{\partial x} - \frac{4z^3}{3h^2}\frac{\partial w_s}{\partial x}$$

$$V(x, y, z, t) = v(x, y, t) - z\frac{\partial w_b}{\partial y} - \frac{4z^3}{3h^2}\frac{\partial w_s}{\partial y} \tag{1}$$

$$W(x, y, z, t) = w_b(x, y, t) + w_s(x, y, t)$$

where u and v are the mid-plane displacements along x and y coordinates, w_b and w_s are the bending and shear components of the transverse displacement and h is the thickness of the plate. The strains associated with the displacement field are

$$\varepsilon_x = \frac{\partial u}{\partial x} - z\frac{\partial^2 w_b}{\partial x^2} - \frac{4z^3}{3h^2}\frac{\partial^2 w_s}{\partial x^2}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} - z\frac{\partial^2 w_b}{\partial y^2} - \frac{4z^3}{3h^2}\frac{\partial^2 w_s}{\partial y^2}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} - 2z\frac{\partial^2 w_b}{\partial x \partial y} - \frac{8z^3}{3h^2}\frac{\partial^2 w_s}{\partial x \partial y} \tag{2}$$

$$\gamma_{xz} = (1 - \frac{4z^2}{h^2})\frac{\partial w_s}{\partial x}$$

From Eq 2 we can see that the top (z=h/2) and bottom (z=-h/2) surface transverse shear strain is zero which satisfies the stress-free boundary conditions.

Hamilton's principle is used to derive the equations of motion. The principle is stated as below

$$\int_0^T(\delta U+\delta V-\delta K)dt=0 \tag{3}$$

Where δU is the variation of strain energy

δV is the variation of work done

δK is the variation of kinetic energy

These can be evaluated as follows:

$$\delta U=\int\int_{-h/2}^{h/2}(\sigma_x\delta\varepsilon_x+\sigma_y\delta\varepsilon_y+\sigma_{xy}\delta\gamma_{xy}+\sigma_{xz}\delta\gamma_{xz}+\sigma_{yz}\delta\gamma_{yz})dAdZ \tag{4}$$

$$\delta V=\int q\delta(w_b+w_{s)}\mathrm{dA} \tag{5}$$

$$\delta K=\int_V(\dot{u}_1\delta\dot{u}_1+\dot{u}_2\delta\dot{u}_2+\dot{u}_3\delta\dot{u}_3)\rho(z)dAdZ \tag{6}$$

Where q is the transverse load and the detailed information of the theory is given in [18]. Substituting Eqs 4, 5 and 6 into Eq 3 gives the following governing equation of motion:

$$\delta u:\ \frac{\partial N_x}{\partial x}+\frac{\partial N_y}{\partial y}=I_0\ddot{u}-I_1\frac{\partial\ddot{w}_b}{\partial x}-cI_3\frac{\partial\ddot{w}_s}{\partial x} \tag{7a}$$

$$\delta v:\ \frac{\partial N_{xy}}{\partial x}+\frac{\partial N_y}{\partial y}=I_0\ddot{v}-I_1\frac{\partial\ddot{w}_b}{\partial y}-cI_3\frac{\partial\ddot{w}_s}{\partial y} \tag{7b}$$

$$\delta w_b:\ \frac{\partial^2M_x^b}{\partial x^2}+2\frac{\partial^2M_{xy}^b}{\partial x\,\partial y}+\frac{\partial^2M_y^b}{\partial y^2}+q=I_0(\ddot{w}_b+\ddot{w}_s)+I_1\left(\frac{\partial\ddot{u}}{\partial x}+\frac{\partial\ddot{v}}{\partial y}\right)-I_2\nabla^2\ddot{w}_b-cI_4\nabla^2\ddot{w}_s \tag{7c}$$

$$\delta w_s:\ \frac{\partial^2M_x^s}{\partial x^2}+2\frac{\partial^2M_{xy}^s}{\partial x\,\partial y}+\frac{\partial^2M_y^s}{\partial y^2}+\frac{\partial Q_{xz}}{\partial x}+\frac{\partial Q_{yz}}{\partial y}+q=I_0(\ddot{w}_b+\ddot{w}_s)+cI_3\left(\frac{\partial\ddot{u}}{\partial x}+\frac{\partial\ddot{v}}{\partial y}\right)-cI_4\nabla^2\ddot{w}_b-c^2I_6\nabla^2\ddot{w}_s \tag{7d}$$

Where N, M Q are the stress resultants which are evaluated as

$$(N_x,N_y,N_{xy})=\int_{-h/2}^{h/2}(\sigma_x,\sigma_y,\sigma_{xy})dz$$

$$(M_x^b,M_y^b,M_{xy}^b)=\int_{-h/2}^{h/2}(\sigma_x,\sigma_y,\sigma_{xy})zdz$$

$$(M_x^s,M_y^s,M_{xy}^s)=\int_{-h/2}^{h/2}(\sigma_x,\sigma_y,\sigma_{xy})\frac{4z^2}{3h^2}dz \tag{8}$$

$$Q_{xz}=\int_{-h/2}^{h/2}(1-\frac{4z^2}{h^2})\sigma_{xz}dz$$

$$Q_{yz}=\int_{-h/2}^{h/2}(1-\frac{4z^2}{h^2})\sigma_{yz}dz$$

And (z) is the mass density and I_i are the mass inertias

$$I_0,I_1,I_2,I_3,I_4,I_6=\int_{-h/2}^{h/2}(1,z,z^2,z^3,z^4,z^6)\rho(z)dz \tag{9}$$

As, we are employing the FG materials the volume fraction of the each of the fibre arrangement differs and the detailed evaluation of the material properties of the composite are given in the [17].

These governing equations from 7a to 7d are solved using the Navier's approach for simply supported boundary conditions. The analytical solutions are assumed as

$u(x, y, t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} U_{mn} \cos \propto x \sin \beta y$

$v(x, y, t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} V_{mn} \sin \propto x \cos \beta y$

$$w_b(x, y, t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} W_{bmn} \sin \propto x \sin \beta y \tag{10}$$

$$w_s(x, y, t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} W_{smn} \sin \propto x \sin \beta y$$

Where $\alpha = m\pi/a$, $\beta = n\pi/b$, a and b are the plate dimensions.

After solving the governing equations, the equation of motion of the plate can be written as

$$M\ddot{x} + Kx = F(t) \tag{11}$$

Where F(t) is the contact force. This contact force is evaluated using Hertz contact law[19] which develops the equation of the force with contact stiffness and indention. The equation of force according to Hertz is given as

$$F(t) = Kc * \delta^{1.5} \tag{12}$$

Wherein Kc is the contact stiffness given by

$$Kc = \frac{4}{3} E\sqrt{R_i}$$

Where, R_i is the impactors radius and E is calculated by

$$E = \left(\frac{1-v_i^2}{E_i} + \frac{1}{E_2}\right)^{-1}$$

hereinE_i and $v_i$are the young's modulus and Poisson's ratio of the impactor, respectively, and $E_2$is the transverse young's modulus of the target composite plate. The indentation α is defined as the difference between the displacements of the impactor's tip and the target plate at the impact point and can be expressed as

$$\delta(t) = S_i(t) - W_t(t) \tag{13}$$

in which S_i is the displacement of the impactor's tip and W_t is the displacement of the target composite plate at the impact point.

Here, we are not considering the unloading case and regarding the impactor, the equation of motion of impactor is expressed as

$$m_i\ddot{S}_i(t) + F(t) = 0, \quad S_i(0) = 0, \dot{S}_i(0) = V_0 \tag{14}$$

in which m_i and V_0 are the impactor's mass and initial velocity, respectively. On the other hand, the constant average acceleration Newmark time integration method [20] is used to calculate the dynamic response of the target plates and the impactor displacement

3. Results and Discussions

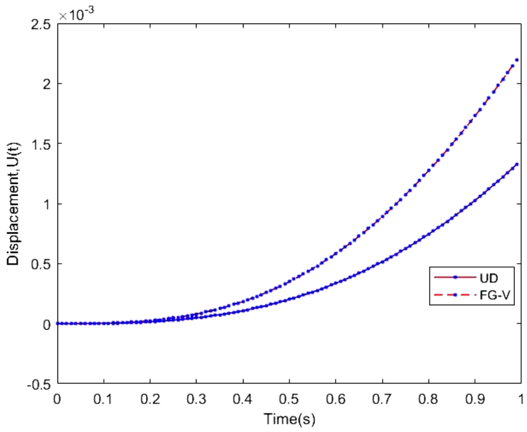
The analytical investigation is carried out on the plate having dimensions a and b with varying length to thickness ratio. The results shown are the transverse displacement of the plate when boundary conditions are applied and the contact force w.r.t time. From authors knowledge, this is the 1st research carried out on the Epoxy reinforced with BNNT composite plate. The governing equations can also be solved using different approaches like Levy's method, Ritz method, FEM etc. For easy computation we have employed the Navier's approach. The plate dimensions and the aspect ratio are taken from [18]. The results taken into consideration are transverse displacement and the contact force as these two values provide the complete energy absorbed by the material.

Table 1 Material Property of Matrix and fibre

Material	Young's modulus	Poisson's ratio	Shear modulus	Radius
Epoxy	3.3GPa	0.48	1.28GPa	-

HDPE	3.2GPa	0.3	0.85GPa	-
BNNT	1180GPa	0.25	500GPa	-
CNT	649.12GPa	0.284	5.13GPa	
Steel Impactor	207GPa	0.3	-	10 mm

Displacement Vs Time Graph



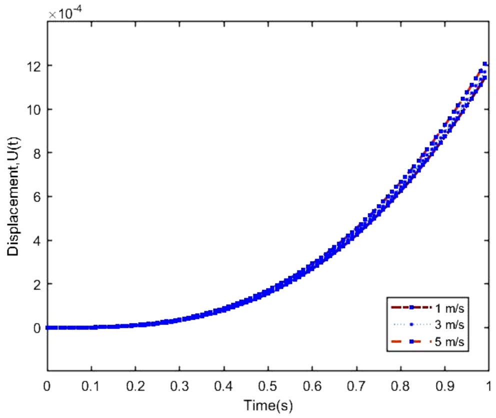
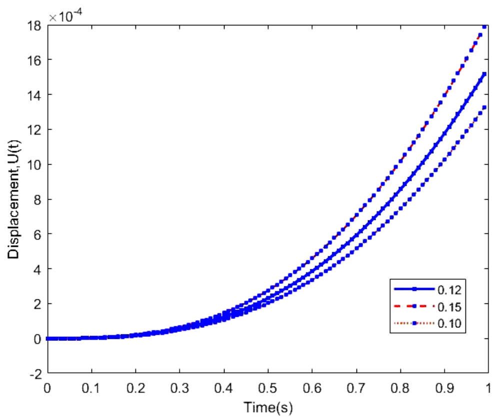


Fig 2&3 represents the graphs based on the type of the distribution of the reinforcment and subjected the impact under different low velocities with plate dimensions a/b=1 and b/h=10



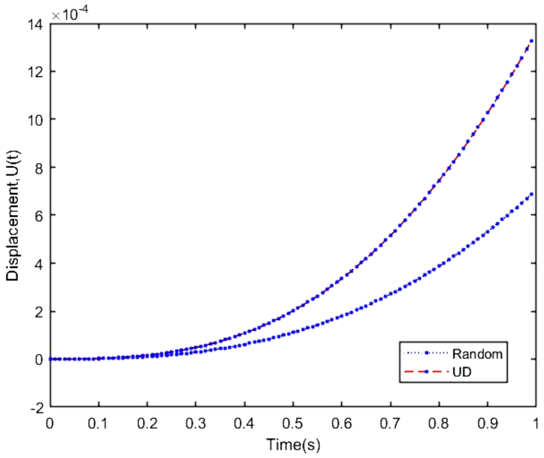
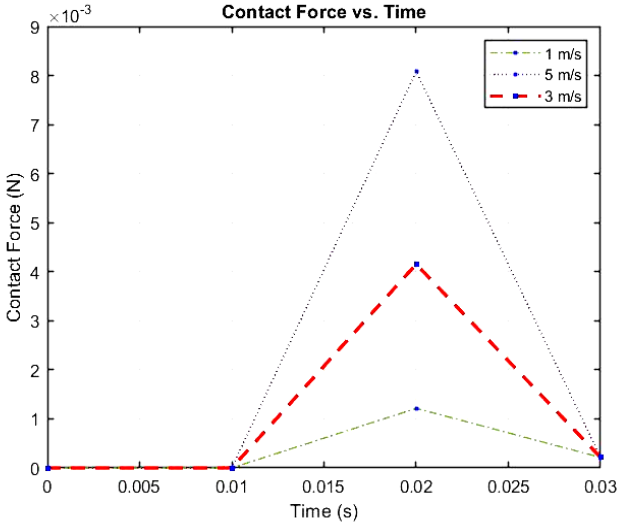


Fig 4&5 Represents the graph based on the different volume fractions and different distributions.

Contact Force Vs Time Graph



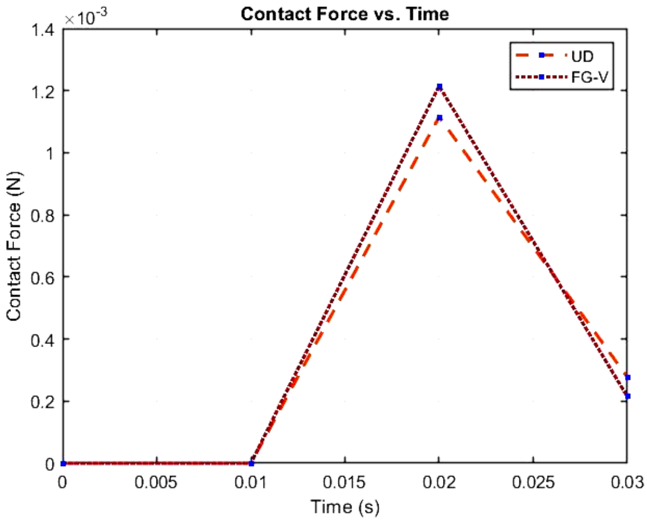


Fig 6&7 represents the graph represents the variation of contact force when the plate is subjected to different velocities and the different arrangement of fibres.

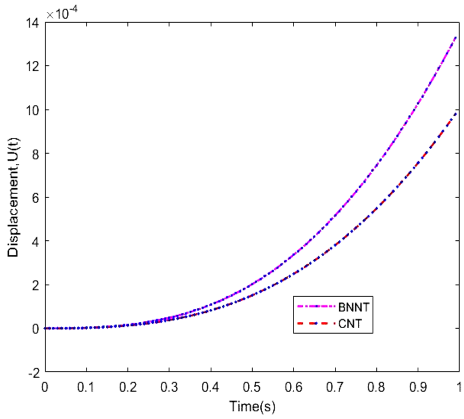


Fig 8 indicated the displacement vs time graph for epoxy-bnnt for volume fraction 0.10 and b/h ratio 10 and

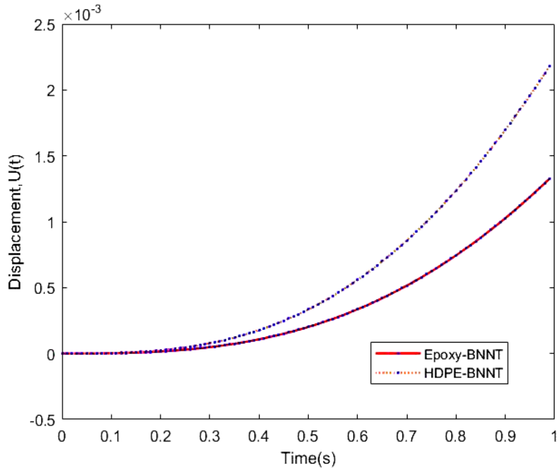


Fig 9 indicates the displacement vs time graph of different BNNT composites i.e., Epoxy and HDPE

4. Conclusion

This research completely defines the dynamic reaction of the plate when low velocity impacts are present. The target plate is composed of epoxy as a matrix and BNNT as reinforcement. The variation in the dynamic response of the plate under different conditions is shown in the fig 2 to 7. The conclusions of the present research are summarized below:

1. The mechanical properties of the Target plate are evaluated for two different orientations of fiber i.e., aligned and randomly oriented and for different arrangements of fiber UD, FG-V, FG-X. [17]
2. The impact response of the target plate under different velocities are evaluated which shows that the influence of velocity on the plate displacement is very low.
3. The influence of volume fraction of the fiber is more on the displacement and contact force of the plate.
4. The orientation of the fiber also influences the dynamic response of the plate.
5. The significance of evaluating the contact force and central deflection of the plate gives us the information about the material absorbed energy level. From the deflection graph we assume that the as deflection the energy absorption is more. And the area under the contact force vs displacement graph gives us the energy absorbed by the material.

The BNNT-epoxy material absorbs more energy than the CNT-Epoxy material

References:

[1] Lai Jiang, WanlinGuo “A molecular mechanics study on size-dependent elastic properties of single-walled boron nitride nanotubes” Journal of the Mechanics and Physics of Solids 59 (2011) 1204–1213.

[2] Eun-Suok Oh “Elastic properties of boron-nitride nanotubes through the continuum lattice approach” Materials Letters 64 (2010) 859–862.

[3] D. VahediFakhrabad, N. Shahtahmassebi “First-principles calculations of the Young’s modulus of double wall boron-nitride nanotubes” Materials Chemistry and Physics 138 (2013) 963e966.

[4] A.GhorbanpourArani, S. Amir “Electro-thermal vibration of visco-elastically coupled BNNT systems conveying fluid embedded on elastic foundation via strain gradient theory” Physica B 419 (2013) 1–6.

[5] A.A. MosallaieBarzoki, A. GhorbanpourArani “Electro-thermo-mechanical torsional buckling of a piezoelectric polymeric cylindrical shell reinforced by DWBNNTs with an elastic core” Applied Mathematical Modelling 36 (2012) 2983–2995.

[6] A.R. Shajari, S. Amir, A. Loghman “Electro-thermo-mechanical nonlinear nonlocal vibration and instability of embedded micro-tube reinforced by BNNT, conveying fluid” Physica E 45 (2012) 109–121

[7] A.GhorbanpourArani, M. Abdollahian, R. Kolahchi , A.H. Rahmati “ Electro-thermo-torsional buckling of an embedded armchair DWBNNT using nonlocal shear deformable shell model” Composites: Part B 51 (2013) 291–299.

[8] Mitesh B. Panchal, S.H. Upadhyay “Cantilevered single walled boron nitride nanotube based nanomechanical resonators of zigzag and armchair forms” Physica E 50 (2013) 73–82.

[9] A.GhorbanpourArani, R. Kolahchi, Z. KhoddamiMaraghi “Nonlinear vibration and instability of embedded double-walled boron nitride nanotubes based on nonlocal cylindrical shell theory” Applied Mathematical Modelling 37(2013) 7685-7707.

[10] A.GhorbanpourArani, M.A. Roudbari “Nonlocal piezoelastic surface effect on the vibration of visco-Pasternak coupled boron nitride nanotube system under a moving nanoparticle” Thin Solid Films 542 (2013) 232–241.

[11] Z. KhodamiMaraghi, A. GhorbanpourArani, R. Kolahchi, S. Amir, M.R. Bagheri “Nonlocal vibration and instability of embedded DWBNNT conveying viscose fluid” Composites: Part B 45 (2013) 423–432.

[12] A.GhorbanpourArani, M. Hashemian, R. Kolahchi“ Time discretization effect on the nonlinear vibration of embedded SWBNNT conveying viscous fluid” Composites: Part B (2013).

[13] Mitesh B Panchal, S. H. Upadhyay, S. P. Harsha “Vibrational Characteristics of Defective Single Walled BN Nanotube Based Nanomechanical Mass Sensors: Single Atom Vacancies and Divacancies” Sensors and Actuators: A Physical (2013).

[14] S T TALEBIAN and M TAHANI “Dynamic response of multiwall boron nitride nanotubes subjected to impact”.

[15] DinhGiaNinh et al “A new study for aeroplane wing shapes made of boron nitride nanotubes-reinforced aluminium, Part I: review, dynamical analyses and simulation” Composite Structures 303 (2023) 116239.

[16] Anant S. Bhatnagar, Ankit Gupta et al “Mean-field homogenization coupled low-velocity impact analysis of nano fibre reinforced composites” Materials Today Communications 26 (2021) 102089.

[17] Ilda Abdollahi, Mohammad Hossein Yas “Free vibration analysis of Timoshenko beams reinforced by BNNTs and a comparison with CNT-reinforced composite” Springer Nature Switzerland AG 2020.

[18] Huu-Tai Thai, Seung-Eock Kim “A simple higher-order shear deformation theory for bending and free vibration analysis of functionally graded plates” Composite Structures 96 (2013) 165–173.

[19] B.A. Selim, L.W. Zhang, K.M. Liew “Impact analysis of CNT-reinforced composite plates based on Reddy’s higher order shear deformation theory using an element-free approach” Composite Structures (2017).

[20] Nathan M. Newmark and F. ASCE “A method of computation for structural dynamics” proceedings for American society of civil engineers.