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STRUCTURAL ANALYSIS OF NANO-FILLER BASED STRUCTURAL COMPOSITE

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Abstract. In this work, we discussed multi-phase composites fabrication and analytical as well as experimental analysis. Shear mixing of MWCNT and epoxy is used to create nanocomposites. Ultrasonication, magnetic stirring, and moulding using the hand layup technique were the following procedures used for sample preparation. Curing and cutting were performed as well, all in accordance with ASTM standards. This research uses an experimental method for assessing material qualities and backs up its findings with an analytical one for verification. It can be shown that the outcomes of both experiments and analyses are consistent. The structural analysis of a composite sample is probed by using a further analytical validation strategy. In this research, we examined the effects of varying the MWCNT content of the matrix. The tensile strength was shown to rise up to 0.5% MWCNT content in the matrix. For 0.7% MWCNT reinforcement in matrix, tensile strength drops as a result of agglomeration. This research also explored the use of ANSYS for critical buckling analysis on many different multi-phase nanocomposites samples. The critical buckling resistance capability of the various configurations of composite materials was examined, and the model's efficacy was shown via validation against existing literature.
Keywords: Prestine CFRP, Hybrid composite, Hybrid marix, Multi-phase composite, buckling analysis

1.Introduction

Nowadays composite materials are widely used in various applications like buildings, bridges, aerospace and satellites due to high strength to wait ratio and good energy absorption characteristics [1]–[6]. The important features of composite materials improved tensile strength, thermal conductivity and corrosion resistance characteristics [7]–[9]. Composite structures are modelled by various techniques namely hand layup, resin transfer moulding, open contact moulding, compression moulding, reaction injection moulding, injection moulding, tube rolling and filament winding and so on [10]–[13]. In the development of nanocomposites carbon nanotube and multi wall carbon nanotube, grapheme and nano silica plays vital role [14].

Quadrini et.al. [15] concluded that 35.7% and 15.1% enhancement was observed in flexural and tensile elastic moduli by the reinforcement of 0.3 wt % CNT as compared with the base sample. Eskizeybeck et. al. [16] noticed that the reinforcement of CNT in glass fibre epoxy decreases the tensile strength and improve the flexural strength. Kaw et.al. [17] were noticed that young’s modulus increased by 82 % by th reinforcement of 5% of MWCNT in to an ultrahigh molecular weight polythene composite film the phenomenon of agglomeration may found in composite material which will cause reduction in mechanical properties.

Agglomeration occurs due to the in ineffective dispersion of enforcement of CNT/graphene etc. in polymer matrix [18]. Many literature shows that the van der Waals force of attraction between nanoparticles agglomerates it. Agglomeration reduces the material properties [19]–[21].

To use the fibre reinforced polymer (FRP) composites in various applications it is important to increase the mechanical properties by the reinforcement of tiny particles called nanofillers in a material to create a mixture with different phases is called multi-phase composites [22]. In FRP matrix has two different purposes:-i) to bind the fibres together during loading ii) load transfer from matrix to fibre during stress concentration. The strength of the matrix is low and to improve the strength of the reinforcement of CNT/graphene is made to create materials that are made up of more than one type of substance or a combination of different materials [5], [23]. Teng and co-authors [24] noticed dynamic vulcanisation process performed on TPI/HDPE hybrid matrix, which results in better improvement in mechanical properties of polymer composites. Toughness, strength and electrical conductivity etc properties are also increased for multi –phase composites by the reinforcement of CNT/graphene etc [25].

Tung et. al. [26] analysed a biaxial compression and conclude that the lowest buckling load effectively observed with a single half wave. [27] analysed the different combinations of m = 1; n = 1,2,3.. and n = 1; m = 1,2,3...and the reults are obtained by applying combinations to the isotropic plates. [28] analysed the buckling strength based on aspect ratio,plate boundry conditions and hole size for the perforated MMC plates with symmetric fibre laminated plates.A. [29] studied the different boundary conditions for laminated plates to investigate the buckling strength, it was observed that non dimensional buckling load under C-C is much high as compered with F-C and C-F boundary conditions. P.F. Pai et.al. [30]carried mode analysis and conclude that the debond of the patch changes the higher mode shapes more as compared to the lower-mode shapes.

The present study focuses on CNTs ability to improve mechanical properties of carbon fibre reinforced polymer CFRP hybrid composites. Proper dispersion of CNT in matrix was made by sonication, magnetic stirring or calendaring [31], [32].The CNT concentrations are taken as 0.1%,0.3%,0.5%,0.7% Bisphenol with aliphatic Amin epoxy with reinforcement of MWCNT used for preparation of multi-phase matrix. The tensile behaviour of the hybrid composites are studied.

The research looks at how strong a special kind of material is by studying analytical and experimental approch for multi-phase hybrid composites.The critical buckling load is also investigated for sample manufactured by analytical approach and validated by ANSYS.

2 Material Properties

High purity MWCNT with external diameter 10 to 15nm and length 5 μm were reinforced with Bisphenol and base epoxy resin with aliphatic amine. The carbon fibre used in 0° ply orientation. The CNT percentage varies as 0.1%, 0.3%, 0.5%, and 0.7%. The properties of matrix carbon fibre and CNT were enlisted below,

Table 1 Material Properties

Material Properties	Epoxy	MWCNT	Carbon Fibre

Modulus of elasticity	3.3 GPa	1.0 TPa	230 GPa
Poisson's ratio	0.4	0.28	0.19
Number of walls	-	2	-

The evaluation of material properties were carried by Halpin-Tsai approach. The properties of three phase material (i.e. matrix, carbon fibre and MWCNT) are important for analytical approach. The properties of three phase laminated structures are reviewed and shortlisted from Lal and Markad [8]. Shape memory polymer composite (SMPC) exhibits the remarkable mechanical properties as compared to its corresponding shape memory polymer (SMP) without compromising the shape memory behavior. The enhancement of the mechanical and thermomechanical properties of the carbon fiber-reinforced SMPC is presented in the present study with the incorporation of graphene nanoplatelets (GnP) in the SMP matrix. The fabrication process involved the preparation of the GnP/epoxy nanocomposites through ultrasonication and shear mixing and the subsequent molding of the carbon fiber-reinforced hybrid polymer composites by hand layup technique. The mechanical and thermomechanical characterizations were conducted as per the ASTM standards, which were followed with corresponding morphological study to the explore the microscale behavior of the hybrid composites. Shape memory behavior were studied in terms of the shape recovery (Rr) and shape fixity (Rf) through the heat activation bending tests. The tensile strength of the hybrid composites with 0.4 and 0.6 wt% GnP content increased by 14.3% and 32.2%, respectively, as compared to unmodified SMPC. Similar trends were also indicated in the dynamic mechanical analysis (DMA) with the corresponding rise in the storage modulus and glass transition temperature due to incorporation of nanofillers. The improvement of the interfacial bonding between the fiber and matrix and wettability of carbon fiber supported these improvements. Negligible adverse effect was noticed in the shape memory behavior of the hybrid composites with the incorporation of GnP, which displayed the Rr and Rf of 97% and 96%, respectively. [5], [8] This paper presents the effect of the variations of multi-walled carbon nanotube (MWCNT) modification in shape memory polymer hybrid composites concerning their mechanical, thermomechanical, and shape memory characterizations. The process of fabrication includes preparation of the MWCNT/epoxy hybrid nanocomposites by shear mixing, ultrasonication, magnetic stirring, and subsequent molding by hand layup method. The appropriate post-processing was performed for the curing and cutting to prepare the samples for the mechanical and thermomechanical characterizations as per the ASTM standards. An enhancement in the thermomechanical properties was noticed due to the incorporation of the MWCNT. These observations were also validated with improvement in the interfacial bonding between the carbon fiber and the modified matrix, as shown in the morphological fractography. The tensile strengths were improved by 18%, 39%, and 26% with the incorporation of 0.4%, 0.6%, and 0.8% modified MWCNT nanocomposites as compared to pure unmodified SMPC. However, the shape recovery of all the configurations of the shape memory polymer hybrid composites was not compromised on polymer-modified remaining almost unchanged at 94% [5], [6]. The elastic modulus of MWCNT can be evaluated from the following equations,

$$Emwcnt = \frac{Wn * tcnt * Eswcnt}{(Wn-1) * hin + tcnt} \tag{1}$$

$$Eecnt = (2 * tcnt * Emwcnt)/rcnt \tag{2}$$

$$Emcnt = \left(\frac{3 * Em}{8}\right) * \frac{\left[\left(1 + GTL * Vcnt * \frac{\left\{\left(\frac{Eecnt}{Em}\right) - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTL\right\}}\right)\right]}{\left[\left(1 - Vcnt * \frac{\left\{\frac{Eecnt}{Em} - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTL\right\}}\right)\right]} + \left(\frac{5 * Em}{8}\right) \frac{\left[\left(1 + GTT * Vcnt * \frac{\left\{\left(\frac{Eecnt}{Em}\right) - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTT\right\}}\right)\right]}{\left[\left(1 - Vcnt * \frac{\left\{\frac{Eecnt}{Em} - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTT\right\}}\right)\right]} \tag{3}$$

$$Gmcnt = \left(\frac{Em}{8}\right) * \frac{\left[\left(1 + GTL * Vcnt * \frac{\left\{\left(\frac{Eecnt}{Em}\right) - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTL\right\}}\right)\right]}{\left[\left(1 - Vcnt * \frac{\left\{\frac{Eecnt}{Em} - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTL\right\}}\right)\right]} + \left(\frac{Em}{4}\right) * \frac{\left[\left(1 + GTT * Vcnt * \frac{\left\{\left(\frac{Eecnt}{Em}\right) - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTT\right\}}\right)\right]}{\left[\left(1 - Vcnt * \frac{\left\{\frac{Eecnt}{Em} - 1\right\}}{\left\{\frac{Eecnt}{Em} + GTT\right\}}\right)\right]} \tag{4}$$

$$\mu mcnt = \frac{Emcnt}{2 * Gmcnt} - 1 \tag{5}$$

$$GTL = \frac{2 * l}{d} \tag{6}$$

$$E1 = (Ef * Vf) + (Emcnt * Vm) \tag{7}$$

$$\mu 12 = (\mu f * Vf) + (\mu mcnt * Vm) \tag{8}$$

$$E2 = Em = \frac{\left[\left(1 + 2 * Vf * \frac{\left\{\left(\frac{Ef}{Em}\right) - 1\right\}}{\left\{\frac{Ef}{Em} + 2\right\}}\right)\right]}{\left[\left(1 - Vf * \frac{\left\{\frac{Ef}{Em} - 1\right\}}{\left\{\frac{Ef}{Em} + 2\right\}}\right)\right]} \tag{9}$$

$$G12 = G23 = Gm = \frac{\left[\left(1 + Vf * \frac{\left\{\left(\frac{Gf}{Gm}\right) - 1\right\}}{\left\{\frac{Gf}{Gm} + 1\right\}}\right)\right]}{\left[\left(1 - Vf * \frac{\left\{\frac{Gf}{Gm} - 1\right\}}{\left\{\frac{Gf}{Gm} + 1\right\}}\right)\right]} \tag{10}$$

$$\mu 23 = \mu m = \frac{\left[\left(1 + Vf * \frac{\left\{\left(\frac{\mu f}{\mu m}\right) - 1\right\}}{\left\{\frac{\mu f}{\mu m} + 1\right\}}\right)\right]}{\left[\left(1 - Vf * \frac{\left\{\frac{\mu f}{\mu m} - 1\right\}}{\left\{\frac{\mu f}{\mu m} + 1\right\}}\right)\right]} \tag{11}$$

3 Sample Preparation

In this work two types of samples were prepared

1. Pure CFRP
2. CFRP with reinforcement of MWCNT

3.1 Preparation of CFRP

For preparation of CFRP hand layup technique was used. Initially Carbon fibres were laid on the mould and then epoxy resin was applied on fibres as per guidelines of manufacturer epoxy resin and hardener mixing ratio is maintained at 100:10. In hand layup technique excessive resins can be extracted by roller moving in the direction of fibre orientation. By pressing roller over the fibre along with excessive resins voids also get removed. Uniform pressure is applied on the sample and kept it for 24 hours at room temperature. In the next part of curing, sample is heated up to 80°C in oven which will help to remove air trapped in the sample during preparation [5], [6]. The volume fraction of carbon fibre is maintain at 28% it will ensure the interferential bond between fibre and epoxy matrix.

3.2 Preparation of CFRP with MWCNT reinforcement

Initial MWCNT were dispersed in 100 ml acetone and stirred it for 1 hour and then followed by sonication for 10 minute. The purpose of this mixing is to do de-agglomeration of MWCNT nanoparticles. In sonication process temperature may rises to undesirable level that may cause rupture of walls of nanoparticles therefore it is necessary to keep the specimen surrounded by icebath. The sonicated mixture i.e. acetone and MWCNT added to epoxy resin and stirred at 2000 rpm at 85 °C ,during this the acetone was turned into a gas and went away from the mixture. The remaining mixture is again sonicated for 1 hour which will cause uniform distribution of MWCNT in resin. After sonication process the mixture is kept in vacuum chamber for 24 hours to release air bubbles from the mixture which will be created by sonicator. The hardener was added in the mixture of resin and MWCNT which will stirred for 10 minute. 5 layered specimen were prepared by varying weight percentage of MWCNT as 0%,0.1%,0.3%,0.5% and 0.7% etc. later on samples were machined by abrasive water jet machine for required tensile test. Schematic represention of fabrication of CFRP with MWCNT shown in figure 1.

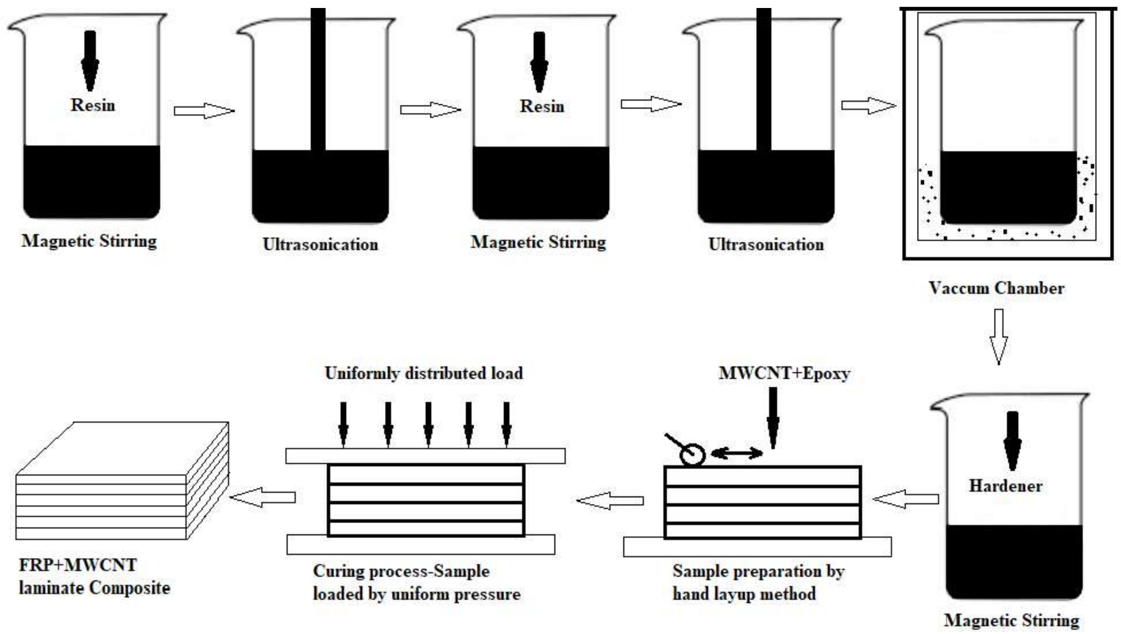


Fig.1 Schematic diagram to represent fabrication of CFRP with MWCNT

4. Experimental Set up

Tensile test were carried on nanoparticle composites sample as per ASTM D 3039. Sample dimensions are 150mm X 20mm X 1.8mm which was performed on Instron UTM 5582. By resin burn off test fibre volume fraction and voids were determined. The test is as per ASTM D 3171-99 standard. Initial weight of samples were measured and then after burn of test again weight is measured. The burning process was carried at 625°C.

5. Results and discussion on material properties evaluation by experimental and analytical method

5.1 Fibre volume fraction

Fibre volume fractions are shown in figure 2. The void content of the sample causes a noticeable shift in the volume fraction. These crevices appeared in a vacuum chamber while storing a sonicated sample of epoxy resin enhanced with MWCNT. Not all Bubbles are destroyed before they reach the matrix [6], [33]. The carbon fiber's volume proportion stayed about the same, at around 28%.

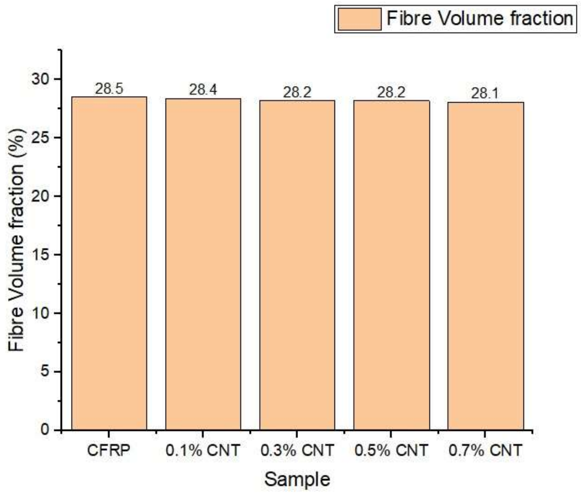


Fig.2 Fiber volume fraction in CFRP with MWCNT

5.2 Tensile test

The force-displacement plot varies according to the proportion of MWCNT used to strengthen the sample, as seen in the figure. As can be shown in figure 3, the MWCNT-reinforced polymer has a higher load bearing capability than the CFRP sample. Modified nanocomposites containing 0.1%,0.3%,0.5%, and 0.7% MWCNT increased tensile strength by 9%, 17%, 35%, and 26%, respectively, as compared to pure CFRP. Tensile parameters including as maximum force, elasticity, and poisons ratio all improved with increasing CNT % as shown in figures 4 and 5.

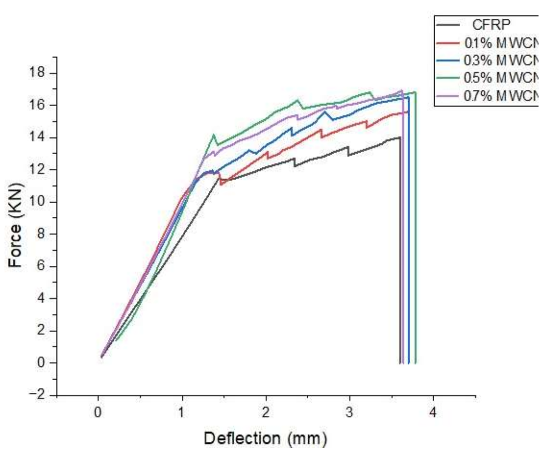


Fig. 3 Tensile behaviour of reinforced sample containing varying % of MWCNT showing force vs deflection

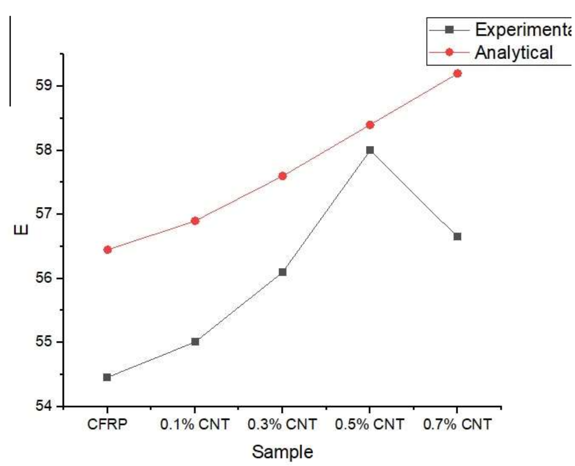


Fig. 4 Modulus of elasticity for reinforced sample containing varying % of MWCNT

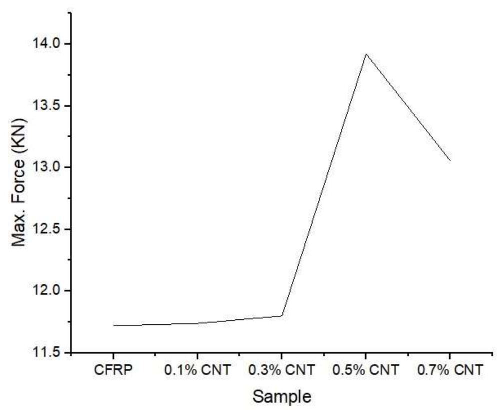


Fig. 5 Force carrying capacity of reinforced sample containing different % of MWCNT

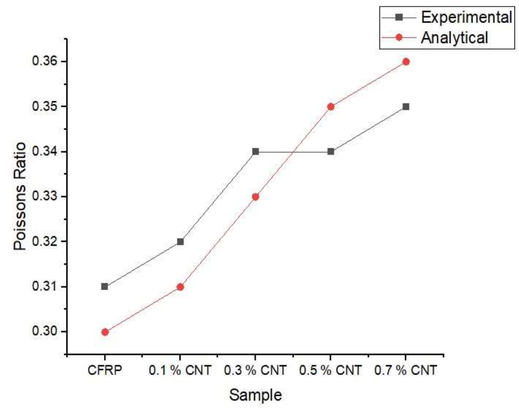


Fig. 6 Poisson's ratio of reinforced sample containing different % of MWCNT

The 0.7% MWCNT sample showed a decrease in tensile strength compared to the 0.5% MWCNT sample. This runs counter to the trend of rising interfacial tension between CNTs and their supporting matrix. The MWCNT aggregation in the matrix was a major factor in this [34]. Because of the potential for agglomeration, MWCNT should not be introduced in excess of a certain concentration. Figure 6 contrasts the elastic characteristics determined experimentally with those determined analytically. The existence of voids or agglomerated nanoparticle bundles in the matrix accounts for the little amount of variance seen in the findings. 0.7% of the MWCNT reinforced sample showed a significant drop in mechanical characteristics, which was traced to the onset of agglomeration..

6. Buckling Analysis of structural composites

The amount of carbon nanotubes (CNTs), plate thickness, fibre orientation, and boundary condition all have a role in the force required to cause a laminated plate to buckle [35]. Most loads are carried by continuous fibres aligned parallel to the direction of force acting. In this study, we use both an analytical technique and a finite element method to determine the critical buckling stress for a fiber-reinforced material with a changing fraction of carbon nanotubes. For the buckling analysis, a simply supported boundary condition is used with the fibre orientation of the laminated plates held constant at 0 degrees and a compressive line pressure of 1 N/mm supplied. The characteristics of the S-S-S-S boundary condition are shown in figure 7.

6.1 Analytical Approach for buckling analysis

The rectangular plate of lenth *a*, width *b* and thickness *h* is acted by a simply supported conditions on each edge as shown in figure 7. A uniformly distributed load is applied in unidirection.The boundry conditions applied are as folows.

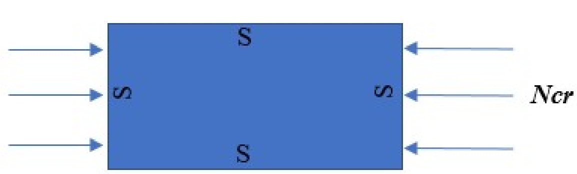


Fig. 7 Schematic representation of simply supported edges with buckling load

The governing equation for the nonlinear static analysis is,

$$[K]\{q\} = \lambda[Kg]\{q\} \qquad [12]$$

Where,

{q}=Transverse Deflection

$[K] = \{[K_L] + [K_{NL}] + [K_{fL}] + [K_{fNL}]\}$

The stiffness matrix [K] is a group of different stiffness matrices that are used to measure how stiff a beam or foundation is, and there is also a geometric stiffness matrix $[K_g]$ included. The solution to equation number 12, can get using methods like direct iterative, incremental, or Newton-Raphson. The Newton Raphson method is a fast and popular way to solve problems, especially when the answers are at higher amplitude.

The critical buckling load acting on plate is calculated by following equation [36],

$$Ncr = -(\pi a/m)^2 * (D_1*(m/a)^4 + 2*D_3*(m/a)^2(n/b)^2 + D_2*(n/b)^4) \qquad [13]$$

Where,

$$m = \textit{Half wave number along transverse direction}$$

$$n = \textit{Half wave number along longitudinal direction}$$

'D' values are calculated as follows,

D1= D11 ; D2= D22 ; D3= D12 + 2*D66

$$D_{ij} = \begin{bmatrix} D11 & D12 & D16 \\ D12 & D22 & D26 \\ D16 & D26 & D66 \end{bmatrix}$$

Dij= (1/3) * $\sum_{k=1}^{n}(Qij)$k * [(h^3)k-(h^3)k-1]

$Q11 = Q11 *m^4 + 2*(Q12 + 2*Q66)\, m^2n^2 + Q22 * n^4$

$Q12 = Q12 *(m^4 + n^4) + (Q11 + Q22 - 4*Q66)\, m^2n^2$

$Q22 = Q11 *n^4 + 2*(Q12 + 2*Q66)\, m^2n^2 + Q22 * m^4$

Q11=(E11/(1-μ12*μ21))

Q22=(E22/(1-μ12*μ21))

Q12=Q21=(E11* μ21/(1-μ12*μ21))

Q66=G12

6.2 Finite element model for buckling analysis

A total of 1183 nodes and 1080 elements were used in finite element analyses. Critical buckling loads (Nx,cr) were obtained from composite plate for first mode shape (i =1)of each sample that is CFRP and CFRP reinforced with varying percentage of CNT.The boundry conditions applied are as shown in figure 8.

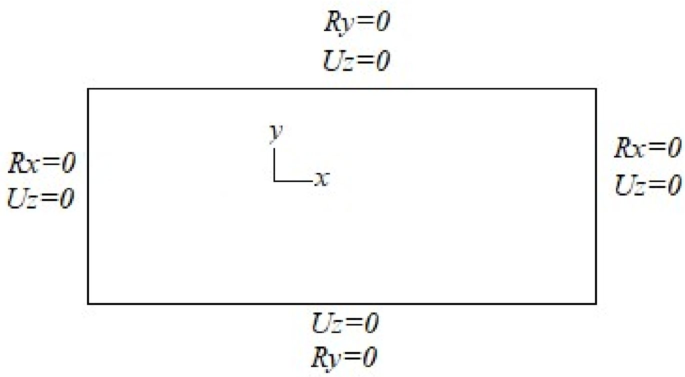


Fig. 8 Boundry condition for FEA model

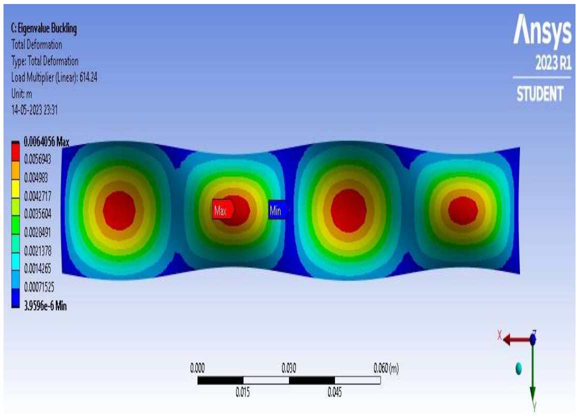
6.3 Results and discussion of buckling analysis

The critical buckling load for first mode shape of various sample prepared was evaluated by analytical as well as FEM.The results are enlisted below in Table 1. It is noticed that the results are in good agreement with each other and the error is less than 5%.

Table 1. Comparison of critical buckling load evaluated by Analytical and FEM approach

Sample	**Critical Buckling Load(N)**	
	Finite Element Approach	**Analytical Approach**
CFRP	614.24	609.72
CFRP with reinforcement of 0.1% MWCNT	620.43	619.29
CFRP with reinforcement of 0.3% MWCNT	643.45	641.38
CFRP with reinforcement of 0.5% MWCNT	660.37	658.27
CFRP with reinforcement of 0.7% MWCNT	685.47	678.67

The present analysis is also focused on the buckling mode shape evaluation for the each sample means for the presine CFRP, 0.1% , 0.3%, 0.5% and 0.7% MWCNT content in modified matrix multi-phase samples as shown in figures 9.


C: Eigenvalue Buckling
Total Deformation
Type: Total Deformation
Load Multiplier (Linear): 614.24
Unit: m
14-05-2023 23:31
Ansys
2023 R1
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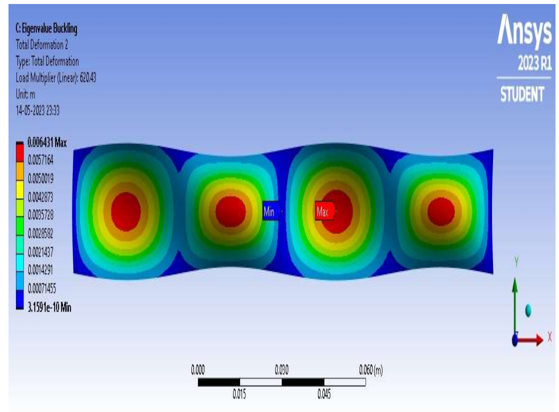
(a)


C: Eigenvalue Buckling
Total Deformation 2
Type: Total Deformation
Load Multiplier (Linear): 620.43
Unit: m
14-05-2023 23:33
Ansys
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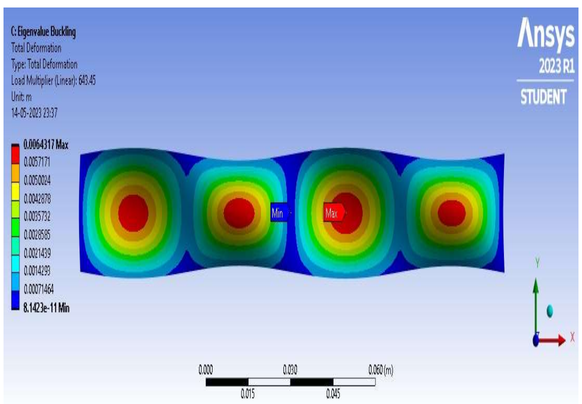
(b)


C: Eigenvalue Buckling
Total Deformation
Type: Total Deformation
Load Multiplier (Linear): 643.45
Unit: m
14-05-2023 23:37
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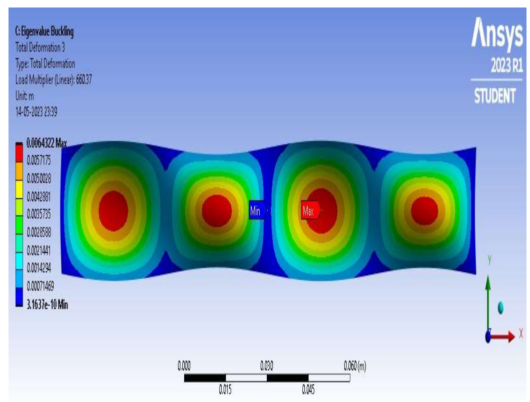
(c)


C: Eigenvalue Buckling
Total Deformation 3
Type: Total Deformation
Load Multiplier (Linear): 660.37
Unit: m
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Ansys
2023 R1
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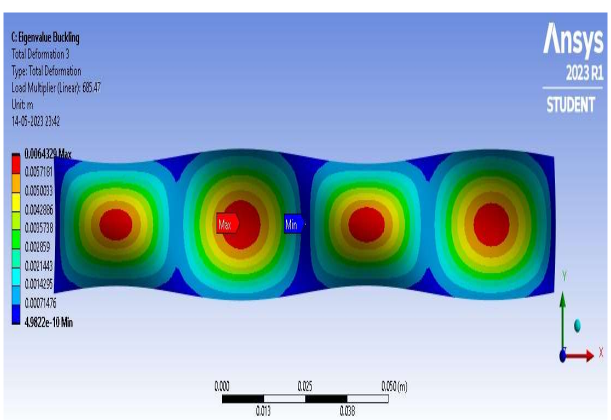
(d)


C: Eigenvalue Buckling
Total Deformation 3
Type: Total Deformation
Load Multiplier (Linear): 685.47
Unit: m
14-05-2023 23:42
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(e)

Fig. 9 buckling mode shape evaluation for (a) the presine CFRP, (b) 0.1% , (c) 0.3%, (d) 0.5% and (e) 0.7% MWCNT content in modified matrix multi-phase

7. Conclusions

There is a strong correlation between experimental and analytical findings. The elastic characteristics have an inaccuracy of less than 5%. Modified nanocomposites containing 0.1%,0.3%,0.5%, and 0.7% MWCNT increased tensile strength by 9%, 17%, 35%, and 26%, respectively, as compared to pure CFRP.The elastic characteristics and load bearing capacity decrease for the 0.7% MWCNT sample.This may occur if the CNT in the mixture clumps together.This article also explored critical buckling analysis of many distinct types of multi-phase nanocomposites. The critical buckling load is found to rise with the % of CNT reinforcement, as predicted by both the analytical result and the FEA result.

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