Effect of nanoparticles loading on free vibration response of epoxy and filament winding basalt/epoxy and E-glass/epoxy composite tubes: experimental, analytical and numerical investigations

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Abstract

In recent times, basalt fiber reinforced polymer (BFRP) nanocomposites is being increasingly used in aerospace applications such as wing and fuselage structures of the aircraft and outer casings of the rocket, automobile engine drive shafts and fuel tanks in the oil and gas industries, which fills the gap between carbon and E-glass fiber reinforced polymer nanocomposites. These structures are subjected to vibrations and exposed to different temperatures in various places during their service life. However, the comparison of vibration response of silica particles reinforced basalt/epoxy and glass/epoxy nanocomposite tubes in all three approaches, namely, experimental, analytical and numerical (Finite Element Modeling), have not found elsewhere. Analytical and numerical approaches minimize time, manpower and cost. Therefore, investigating the vibration response of different weight contents of these FRP nanocomposite tubes is novel and essential. Hence, in this study, the vibration response of silica nanoparticles reinforced epoxy, basalt/epoxy and E-glass/epoxy composites with different weight contents (0, 0.5, 1 and 1.5%) were investigated. The vibration tests were performed at three different boundary conditions such as cantilever, simply supported and fixed-fixed. The first three modes of vibration were considered for analysis. Besides, the heat deflection temperature and the hardness properties were also studied. The results indicate that the natural frequencies were higher for the fixed-fixed case and the damping parameters were higher for the simply supported case. Vibration properties, heat deflection temperature and hardness values were found to be higher in fiber-reinforced nanocomposites than those of epoxy nanocomposites. The data presented in this study will be useful to generate the numerical models for the ground vibration test (GVT).

Nomenclature

| E/S/0% | Neat epoxy |
| E/S/0.5% | 0.5 wt% silica filled epoxy |
| E/S/1% | 1 wt% silica filled epoxy |
| E/S/1.5% | 1.5 wt% silica filled epoxy |
| G/S/0% | GFRP |
| G/S/0.5% | 0.5 wt% silica filled GFRP |
| G/S/1% | 1 wt% silica filled GFRP |
| G/S/1.5% | 1.5 wt% silica filled GFRP |
| B/S/0% | BFRP |
| B/S/0.5% | 0.5 wt% silica filled BFRP |
### Table 1. Definitions of Various Symbols

| Symbol | Description                          |
|--------|-------------------------------------|
| B/S    | 1 wt% silica filled BFRP            |
| B/1.5/1.5% | 1.5 wt% silica filled BFRP         |
| $E_1$  | Longitudinal modulus of the composite |
| $E_2$  | Transverse modulus of the composite |
| $E_3$  | Through-thickness modulus of the composite |
| $\nu_{12}$ | Major in-plane Poisson’s ratio     |
| $\nu_{23}$ | Minor in-plane Poisson’s ratio     |
| $\nu_{21}$ | Out-of-plane Poisson’s ratio      |
| $E_{V/S}$ | Young’s modulus of epoxy nanocomposites |
| $V_{E/S}$ | Volume fraction of epoxy nanocomposites |
| $\nu_{E/S}$ | Poisson’s ratio of epoxy nanocomposites |
| $G_{E/S}$ | Shear modulus of epoxy nanocomposites |

## 1. Introduction

The use of synthetic fiber reinforced polymer composites (FRPC) for aerospace, automotive, helicopter and marine structural components have been increased in recent times. In particular, the weight percentage of FRPC for aircrafts such as Airbus A350 and Boeing 787 is more than 52% and 50%, respectively [1–3]. This is due to their high strength to weight ratio, good vibration and fatigue properties, excellent corrosion resistance as compared to conventional metals [4–6]. Pankaj et al. [7] reported that the natural frequency of Kevlar fiber reinforced polymer (KFRP) composite shaft is higher compared to a steel shaft. However, it is well known that metals exhibit higher fracture toughness owing to high plastic strain and better thermal properties than that of FRPC. On the contrary, the addition of nanoparticles in the fiber-reinforced polymer (FRP) composites leads to improve both the fracture toughness and thermal properties [8, 9]. In the past, several studies were conducted for understanding the effect of weight fraction and volume fraction of silica particles on mechanical properties of epoxy–silica nanocomposites, and found significant improvement in tensile strength and modulus owing to a better bonding ability of silica particles with epoxy [10, 11]. In particular, in the recent study, the significant improvement in mechanical and thermal properties of FRPC was founded by the addition of silica nanoparticles in it, which can be attributed to increase in the fiber-matrix interfacial bonding due to the dispersion of higher surface roughness of silica nanoparticles [12].

Although the thermal properties of synthetic fiber composites can be improved by the addition of nanofillers in it, additives could be added during synthetic fibers production, which has a toxic reaction with water and air. These synthetic fibers are non-biodegradable, which is harmful to humans and the environment, hence, waste disposal is the major non-resolving issue [13]. Also, the cost of carbon fiber is significantly higher and Young’s modulus and chemical resistance of E-glass fibers are significantly less. On the other hand, no additives are required to manufacture the basalt fiber since being a natural fiber, which is manufactured through igneous basalt rocks melt drawing at approximately 1500°C. As a result, basalt fiber produces no toxic reaction with water and air [14]. The %elongation is high and the cost is significantly lower for basalt fiber than the carbon fiber [15, 16]. The basalt fiber possesses high mechanical, thermal and vibration damping properties which can be attributed to a higher amount of aluminum oxide and iron oxide content, than the E-glass fiber for almost the same cost [17, 18]. Besides, the electrical resistance of glass fibers is, 10 times lower than the basalt fibers, as a result, basalt fibers are utilized for electrical applications such as circuit boards, wires, etc, [19]. Moreover, basalt rock is about one-third of Earth’s crust, therefore, basalt fiber is durable and exhibits high fracture toughness than carbon and glass fibers [20]. Therefore, in recent times, BFRP composites have been widely used owing to the above-mentioned merits, for fabricating aircraft wing and fuselage, civil bridges and arches, automobile drive shafts, helicopter rotor systems, etc, [21, 22]. However, these structures are subjected to dynamic loads and acoustic vibrations during their service life [23]. Hence, it is essential to study the vibration properties of FRPC in different modes and end conditions. These vibration properties will also be useful for ground vibration test (GVT) which is commonly performed test in aircraft industries for certifying the new or heavily modified aircraft, based on the dynamic aeroelastic performance of the aircraft [24].

FRP plates subjected to different modes and end conditions of vibration were studied in the past by several researchers. Alexander et al. [25, 26] studied the vibration behavior of BFRP and glass fiber reinforced polymer (GFRP) composite plates of different fiber orientations at different boundary conditions. The vibration characteristics of BFRP composites were found to be higher than the GFRP composites. Bozkurt et al. [27]
reported that BFRP composites exhibit higher values of damping and lower values of natural frequency compared to GFRP composites. Madhu and Kumaraswamy [28] studied the vibration response of carbon/epoxy and glass/epoxy composites, experimentally and numerically. They performed the modal analysis using Ansys 15 APDL for predicting the first three modes of the natural frequency and compared the results with the experiments. Carbon/epoxy composites exhibited higher natural frequencies compared to glass/epoxy composites. Alsaa di et al [29] performed the vibration tests on different weight contents (0, 0.5, 1, 1.5, 2.5 and 3%) of nano-silica particles included twill weave intra-ply carbon/Kevalr hybrid composites. The natural frequency was found to be higher for nanocomposites of 0.5 wt% while the damping factor was found to be higher for nanocomposites of 0 wt% followed by 3 wt%. In a recent study, Bulut et al [30] studied the vibration behavior for the first two modes on basalt/epoxy composites reinforced with various weight contents (0 to 0.3%) of graphene nanofillers. It was found that the natural frequency and damping ratio increased up to 0.3 wt% addition of graphene nanofillers in BFRP. Surana et al [31] investigated the effect of sawdust particles ranging from 0 to 6 wt%, on the vibration behavior of BFRP composites. The increase in natural frequency and decrease in damping factor values were found, as the sawdust particles content increases from 0 to 6 wt% in BFRP composites. Chandradas et al [32] conducted the free vibration test on glass/epoxy/OMMT (organically modified montmorillonite) clay nanocomposites of different weight percentages (0, 1, 3 and 5). These tests were carried out by clamping the specimens to fixed-free end conditions to estimate the natural frequency and damping factor for the first four modes of vibration. The results indicated that the frequency and damping factor increase for nanocomposites of up to 3 wt% and then decrease with the increase in nanoclay content. Babu et al [33] studied the natural frequency and damping ratios of GFRP reinforced fly ash with different weight percentages (0, 5, 10, 15 and 20%) and found that these properties were higher for composites with the fly ash addition of 5 wt%. The decrease in vibration properties of composites having of the high content of fly ash is owing to stress concentrations induced in the polymer matrix which can be attributed to the agglomeration of particles.

1.1. Problem statement and methodology
The failure of the component normally takes place when the components reach the resonant frequency. Therefore, it is important to avoid the resonant condition by increasing the deviation between the excitation frequency and the natural frequency. Also, the amplitude of the vibration of the composite structure can be controlled by providing the required amount of damping to it, for avoiding the resonance and therefore, to protect the structure from the failure [34]. Although there are several studies [35–40] on the mechanical and pressure bursting behavior of FRP tubes and its nanocomposites, the vibration characterization studies of FRP nanocomposite tubes (FRPNCTs) are limited. Moreover, there is no literature has investigated for vibration response of BFRP nanocomposite tubes. Hence, an understanding of the vibration response (natural frequency and damping ratio) of FRPC at different modes and end conditions is essential.

In the present work, a new attempt is given to study the free vibration characteristics of filament winding FRP/silica nanocomposite tubes experimentally, analytically and numerically using Ansys. The vibration response for three different end conditions include cantilever, simply supported and fixed-fixed were studied. This work is novel and it is the first paper that covers all three formats of vibration response of FRPNCTs. These results are compared with epoxy/silica nanocomposites fabricated by a resin casting process. Also, the heat deflection temperature and hardness behavior of the above-mentioned materials were experimentally studied. These properties will be useful to GVT and the designing of pipes and pressure vessels. These are graphically presented in figure 1. The excellent corrosion resistance of these FRPNCTs leads to the long term durability, and hence, the maintenance cost of the component can be significantly reduced to customers.

2. Materials selection and specimen fabrication
Reinforcing materials such as glass and basalt fibers, and matrix materials such as an epoxy resin (LY556) and hardener (Aradour- HY 951), and silica nanoparticles were used in the present work. The density of silica nanoparticles and epoxy are 2.5 g cm$^{-3}$ and 1.2 g cm$^{-3}$, respectively. Different weight contents (0, 0.5, 1 and 1.5%) of silica nanoparticles were incorporated in epoxy and FRPC to fabricate nanocomposite plates and tubes, respectively.

Initially, epoxy nanocomposite plates were prepared using resin a casting process. Resin to hardener ratio was taken as 10:1, by weight, as per manufacturer data sheet. Before adding hardener into epoxy resin, the nanoparticles were well dispersed in epoxy for about 30 min using a magnetic stirrer. The uniform dispersion of nanoparticles in resin was assessed by using field emission scanning electron microscopy (FESEM). Further, FRPNCTs of ±45° fiber orientation were fabricated using the filament winding process. These tubes were post
cured for 48 h, before performing experiments. Figure 2 illustrates the fabrication procedure for both epoxy nanocomposite plates and FRPNCTs.

3. Experimental details

3.1. Vibration test setup

Figures 3 and 4 represent the free vibration setup consisting of a Fast Fourier Transforms (FFT) analyzer, accelerometer (Kistler model 8776A50) for output signal and impact hammer (Kistler model 9712B50) to excite the vibration on the specimen. Vibration tests were conducted using this setup, on epoxy, basalt/epoxy and...
glass/epoxy nanocomposites of different silica particle loading (0, 0.5, 1 and 1.5 wt%). These tests were conducted in three different end conditions, namely, fixed-fixed, cantilever and simply supported.

Initially, free vibration was excited on the sample using the impact hammer. The resulting vibrations of the specimen were measured by the accelerometer which was mounted on the specimen using wax. The function of the accelerometer is to convert the physical motion given to the specimen by impact hammer to an electronic signal, and the analyzer subsequently received the signals from accelerometer through data acquisition (8 channel DAQ), where its frequency response was generated. The information was further channeled to DEWESOFT software using a power adaptor and then the properties such as natural frequency and damping factor were displaced in the computer.

### 3.2. Heat deflection temperature (HDT)

HDT tests were performed on rectangular specimens of epoxy, basalt/epoxy and glass/epoxy nanocomposites of different weight percentages using the HDT machine. These tests were performed as per ASTM D648. The width, thickness and span length of the specimen between the supports used for this test were 13 mm, 3 mm and 101 mm, respectively. The specimen was placed in an HDT fixture of three-point bending mode (simply supported) and applied the heating rate of 2 °C min⁻¹. The load was applied at the center of the specimen until the deflection reaches to 0.25 mm. The temperature at that point of 0.25 mm deflection was recorded, which is the HDT of material.
3.3. Barcol hardness
Estimation of surface hardness values is an important mechanical property for nanocomposite structures. Hardness values for the different weight content of silica particles reinforced epoxy, basalt/epoxy and glass/epoxy nanocomposites were measured using a Barcol hardness instrument as per ASTM D2583. Five readings were taken for each specimen by placing the instrument on five different places of the specimen.

3.4. Crystallographic characterization
The x-ray diffraction (XRD) analysis was carried out using the Aeris high resolution bench top XRD instrument by Malvern Pananalytical. The 2θ values of nano-silica, epoxy, GFRP, BFRP and their nanocomposites were measured in the range from 10° to 100° using for investigating the dispersion of nanoparticles in the epoxy matrix. The scanning of samples was performed at 2° min⁻¹.

4. Procedure for estimating vibration properties in analytical and numerical approaches

4.1. Analytical modeling
4.1.1. Modified rule of mixtures approach
The elastic constants and Poisson’s ratio values for FRP nanocomposites can be written in terms of equivalent properties [combination of epoxy and nanofiller (E/S)] from the modified rule of mixtures [41, 42]. The in-plane modulus and Poisson’s ratio (ν₁₂) expressions for FRP nanocomposites are given by

\[
E_1 = E_f V_f + E_{E/S} V_{E/S}
\]

\[

\nu_{12} = \nu_f V_f + \nu_{E/S} V_{E/S}
\]

where, \(E_f\) is Young’s modulus of the fiber; \(E_{E/S}\) is Young’s modulus of the epoxy/silica; \(\nu_f\) and \(\nu_f\) are the Poisson’s ratio and volume fraction of fiber, respectively; \(V_{E/S}\) and \(V_{E/S}\) are the Poisson’s ratio and volume fraction of epoxy/silica, respectively; The transverse modulus \(E_2\) and shear modulus \(G_{12}\) expressions for FRP nanocomposites can be written in terms of equivalent properties, which can be given by [43]

\[
E_2 = \frac{E_f E_{E/S}}{E_{E/S} V_f + E_f V_f}
\]

\[
G_{12} = \frac{G_f G_{E/S}}{G_{E/S} V_f + G_f V_f}
\]

Similarly, the out-of-plane shear modulus \(G_{23}\) and Bulk modulus are given by [44, 45]

\[
G_{23} = \frac{E_{22}}{2(1 + \nu_{23})}
\]

\[
K = \frac{E_t E_m}{3 \left[ V_f (1 - 2\nu_f) E_m + V_m (1 - 2\nu_m) E_f \right]}
\]

where, \(\nu_{23}\) and \(K\) are the out-of-plane Poisson’s ratio and Bulk modulus of the composite, respectively; \(\nu_{23} = 1 - \nu_{21} - \frac{E_3}{K}\);

4.1.2. Modal analysis
The natural frequency expressions for different boundary conditions and corresponding first three modes of vibration of composites are given in equations (7)–(15) [46].

4.1.2.1. Cantilever
First three modes, i.e., mode I, mode II and mode III of vibration for fixed-free end condition can be calculated using equations (7)–(9), respectively, which are given by [7]

\[
f_1 = (1.758/\pi L^2)\sqrt{(EI/\rho A)} \quad (7)
\]

\[
f_2 = (11.015/\pi L^2)\sqrt{(EI/\rho A)} \quad (8)
\]

\[
f_3 = (30.83/\pi L^2)\sqrt{(EI/\rho A)} \quad (9)
\]

where, \(E, I, \rho\) are Young’s modulus, moment of inertia and density of the nanocomposite, respectively. \(A\) and \(L\) are the area of cross section and span length of the nanocomposite, respectively.
4.1.2.2. Simply supported
First three modes (mode I, mode II and mode III) of vibration for simply supported end condition can be calculated using equations (10)–(12), respectively, which are given by

\[ f_1 = (\pi / 2L^2) \sqrt{EI / \rho A} \]  
\[ f_2 = (2\pi / L^2) \sqrt{EI / \rho A} \]  
\[ f_3 = (9\pi / 2L^2) \sqrt{EI / \rho A} \]

4.1.2.3. Fixed-fixed
The first three modes (mode I, mode II and mode III) of vibration for fixed-fixed end condition can be analytically calculated using equations (13)–(15), respectively.

\[ f_1 = (4.73)^2 \frac{1}{2 \pi L^2} \sqrt{EI / \rho A} \]  
\[ f_2 = (7.832)^2 \frac{1}{2 \pi L^2} \sqrt{EI / \rho A} \]  
\[ f_3 = (14.72)^2 \frac{1}{2 \pi L^2} \sqrt{EI / \rho A} \]

4.2. Finite element analysis (FEA)
The natural frequency for the first three modes of vibration was predicted by employing the finite element modeling method. FRP composite tubes and epoxy plates were modeled using Ansys 15, in which, 8-node brick elements solid 185 was used and three fine mesh was generated. Table 1 represents the input properties used for numerical Modeling, which are calculated from known fiber and epoxy nanocomposite properties obtained from the literature \[12, 47, 48\], via the modified rule of mixtures approach \[equations (1)–(6)\]. The analysis was performed by considering three different boundary conditions, namely fixed-fixed, cantilever and simply supported.

5. Results and discussions
The morphology of SiO2/epoxy, SiO2/glass/epoxy and SiO2/basalt/epoxy was seen in FESEM \[12\], before conducting the vibration, HDT and Barcol hardness tests. Typical scanning electron microscopy (SEM) images for 1.5 wt% silica filled GFRP, BFRP, epoxy and their nanocomposites are shown in figures 5(a)–(c), respectively. As can be seen from these nanocomposites images that the dispersion of nanoparticles is uniform.

Mechanical and physical properties of the epoxy, GFRP and BFRP and their nanocomposites are studied in our previous study \[12\], which are given in table 2. Flexural properties were studied using the Instron universal testing machine. Glass transition temperature (Tg) values were measured using the differential calorimetry (DSC), %wt remaining was measured using the thermo gravimetric analyzer (TGA). Pristine BFRP composites and their nanocomposites possess higher mechanical and %wt remaining, whereas GFRP composites and their nanocomposites possess higher Tg values compared to other nanocomposites.

5.1. Vibration analysis
In this section, the vibration properties of the various weight content of silica particles included epoxy and FRP nanocomposites, for different boundary conditions are presented and discussed.

| Engineering properties | G/S 0% | G/S 0.5% | G/S 1% | G/S 1.5% | B/S 0% | B/S 0.5% | B/S 1% | B/S 1.5% |
|------------------------|--------|----------|--------|----------|--------|----------|--------|----------|
| E1         | 32.504 57 | 30.377 02 | 40.221 17 | 42.721 91 | 38.794 85 | 43.506 20 | 48.131 12 | 51.208 92 |
| E2         | 9.999 415 | 10.294 03 | 12.741 81 | 12.893 28 | 10.488 24 | 10.789 34 | 13.402 32 | 13.550 15 |
| E3         | 9.999 415 | 10.294 03 | 12.741 81 | 12.893 28 | 10.488 24 | 10.789 34 | 13.402 32 | 13.550 15 |
| G12       | 3.630 02 | 3.748 581 | 5.102 554 | 5.197 573 | 3.610 707 | 3.721 608 | 5.008 971 | 5.096 034 |
| G23       | 3.670 529 | 3.531 06 | 5.460 401 | 5.170 09 | 3.897 573 | 3.731 237 | 5.922 363 | 5.566 217 |
| G13       | 3.670 529 | 3.531 06 | 5.460 401 | 5.170 09 | 3.897 573 | 3.731 237 | 5.922 363 | 5.566 217 |
| v12       | 0.308 862 | 0.298 225 | 0.220 000 | 0.215 582 | 0.301 938 | 0.290 27 | 0.209 704 | 0.204 511 |
| v23       | 0.362 122 | 0.457 64 | 0.166 747 | 0.246 911 | 0.345 484 | 0.445 813 | 0.131 501 | 0.217 178 |
| v13       | 0.362 122 | 0.457 64 | 0.166 747 | 0.246 911 | 0.345 484 | 0.445 813 | 0.131 501 | 0.217 178 |
5.1.1. Effect of nanoparticles addition on the natural frequency of epoxy and FRP composites

The modal analysis was performed in three different boundary conditions (fixed-fixed, cantilever and simply supported) using Ansys for predicting the modal frequencies of epoxy nanocomposites and glass/epoxy and basalt/epoxy nanocomposite tubes. The first, three-mode shapes for epoxy, glass/epoxy, basalt/epoxy and their nanocomposites weight content of 1.5%, are shown in figures 6–8, respectively. Here, the first three modes for different boundary conditions are presented for each material. However, simulated images for all boundary conditions are presented in appendix for clarification. A comparison of natural frequency values between each material for each mode and each boundary condition, obtained from the numerical approach is given in table 2.

Figure 5. SEM micrographs for nanocomposites: (a) 1.5 wt% silica/GFRP, (b) 1.5 wt% silica/BFRP and (c) 1.5 wt% silica/epoxy.

Table 2. Mechanical and Physical properties for different weight contents of nanocomposites.

| Material type | Flexural strength (MPa) | Flexural strain (%) at peak load | Flexural modulus (GPa) | Glass transition temp. (°C) | Initial weight (mg) | %wt remaining | Final weight (mg) | %wt remaining |
|---------------|-------------------------|---------------------------------|------------------------|-----------------------------|-------------------|---------------|------------------|---------------|
| E/S 0%        | 67.7 ± 3.12             | 2.03 ± 0.70                    | 2.75 ± 0.71            | 101.90                      | 2.515             | 100%          | –0.002           | –0.0827       |
| E/S 0.5%      | 69.9 ± 0.95             | 2.30 ± 0.10                    | 3.0 ± 0.07             | 125.02                      | 3.194             | 100%          | 0.020            | 0.635 105     |
| E/S 1%        | 70.46 ± 3.71            | 2.16 ± 0.25                    | 3.2 ± 0.1              | 130.20                      | 3.194             | 100%          | 0.247            | 7.742 18       |
| E/S 1.5%      | 70.55 ± 0.67            | 1.57 ± 0.53                    | 3.35 ± 0.19            | 134.36                      | 2.654             | 100%          | 0.212            | 7.990 79       |
| G/S 0%        | 81.32 ± 9.32            | 3.88 ± 0.75                    | 5.43 ± 0.91            | 134.26                      | 7.041             | 100%          | 4.051            | 57.531         |
| G/S 0.5%      | 85.77 ± 7.46            | 3.62 ± 0.23                    | 7.44 ± 0.59            | 159.69                      | 7.221             | 100%          | 4.924            | 68.202         |
| G/S 1%        | 91.88 ± 10.76           | 3.71 ± 1.12                    | 7.5 ± 0.1              | 161.20                      | 5.459             | 100%          | 3.778            | 69.2486        |
| G/S 1.5%      | 79 ± 9.62               | 3.44 ± 0.65                    | 7.72 ± 1.52            | 170.53                      | 5.874             | 100%          | 3.790            | 64.5239        |
| B/S 0%        | 108.78 ± 8              | 3.74 ± 0.52                    | 9 ± 0.45               | 105.37                      | 7.673             | 100%          | 5.358            | 69.8565        |
| B/S 0.5%      | 109.43 ± 2.45           | 4.49 ± 0.31                    | 9.1 ± 0.1              | 140.29                      | 8.413             | 100%          | 5.979            | 71.0752        |
| B/S 1%        | 132.43 ± 12.82          | 4.86 ± 0.58                    | 9.63 ± 1.23            | 158.15                      | 6.505             | 100%          | 4.609            | 70.8783        |
| B/S 1.5%      | 137.39 ± 13.7           | 4.1 ± 0.20                     | 10.92 ± 0.87           | 168.52                      | 3.28              | 100%          | 2.298            | 70.1607        |

5.1.1. Effect of nanoparticles addition on the natural frequency of epoxy and FRP composites

The modal analysis was performed in three different boundary conditions (fixed-fixed, cantilever and simply supported) using Ansys for predicting the modal frequencies of epoxy nanocomposites and glass/epoxy and basalt/epoxy nanocomposite tubes. The first, three-mode shapes for epoxy, glass/epoxy, basalt/epoxy and their nanocomposites weight content of 1.5%, are shown in figures 6–8, respectively. Here, the first three modes for different boundary conditions are presented for each material. However, simulated images for all boundary conditions are presented in appendix for clarification. A comparison of natural frequency values between each material for each mode and each boundary condition, obtained from the numerical approach is given in table 2. Similar kind of mode shapes was found in KFRP for cantilever case by Pankaj et al [7]. It is clear from these figures that the natural frequency values are increasing in all materials, with the change in mode shapes (first mode to the third mode). This can be attributed to a sharp impact pulse associated due to a higher amplitude of vibration for mode 3.
It can be seen from figures 6(a)–(c) that the natural frequency value of neat epoxy increases from 12.9128 Hz to 87.463 Hz, with the increase in mode shape from 1 to 3. The natural frequency values are higher for 1.5 wt% SiO$_2$/epoxy composites compared to neat epoxy which can be seen from figures 6(a) and (d), (b) and (e) and (c) and (f) corresponding to 1st mode, 2nd mode and 3rd mode, respectively. Nanoparticles make the structure stiff, which is the reason for the enhancement in natural frequency. A similar kind of trend was observed from figures 7 and 8 for pristine GFRP and BFRP compared to their nanocomposites.

The analytical values were determined using equations (7)–(15) for the corresponding boundary conditions. Numerically and analytically predicted values were compared with experimental values, and are given in table 3. Table 3 indicates relatively higher natural frequency values for three different end conditions of 1.5 wt% silica particles reinforced glass/epoxy composites and lower for neat epoxy. A significant improvement in natural frequency was observed, by the addition of nanoparticles in epoxy and composites. The reason for this
increment would be due to stiffening the structure induced by nanoparticles. This is the advantage of adding a lower amount of nanoparticles up to 1.5 wt%. On the other hand, a higher amount of nanoparticles induces agglomerations in the matrix, as a result, matrix embrittlement occurs, which can degrade the mechanical and vibration properties \[33, 49\]. It is important to note from the table that the boundary conditions have a strong influence on the natural frequencies of nanocomposites. For the same mode shapes, the natural frequency values were found to be higher for the fixed-fixed case and lower for the cantilever case among the three boundary conditions. Similar kind of observations was found elsewhere \[25\]. This can be attributed to variation in the stiffness of the vibration system induced by different end conditions. A close agreement is observed between the experiments and analytical and numerical predictions.

5.1.2. Effect of nanoparticles addition on damping characteristics of epoxy and FRP composites

The effect of nanoparticles addition on the damping factor (\(\xi\)) of epoxy and FRP nanocomposites was studied. The damping factor values of nanocomposites, for one end fixed, simply supported and fixed-fixed boundary
conditions are shown in figures 9–11, respectively. Specimens tested by simply supported end condition (figure 9) exhibit higher damping factor values compared to specimens with those tested using other end conditions. Similar kind of findings was seen in [25]. It is clear from these figures that the damping factor value increases with the increase in nanoparticle content, which confirms the robustness of nanoparticles addition in epoxy and FRP composites for enhancing vibration characteristics. This can be attributed to an increase in interfacial friction between the epoxy matrix and nanoparticles [50]. A similar kind of trend was found by Bulut et al [30] for graphene nanofillers incorporated basalt/epoxy composites. Lower damping factor values were observed from these figures in the third mode compared to the first and second modes of vibration.

It was also observed from figures 9–11 that damping factor values were higher for epoxy and its nanocomposites compared to FRP nanocomposites. Though the damping factor of epoxy nanocomposites is higher, these nanocomposites cannot be used for primary structural applications, due to their less stiffness compared to FRP nanocomposites [12]. On the other hand, BFRP nanocomposites exhibit similar magnitude of
Table 3. Natural frequency values for different modes and boundary conditions of nanocomposites.

| Materials Methodology | MODE 1 | MODE 2 | MODE 3 |
|-----------------------|--------|--------|--------|
| G/S0% Analytical     | 6.17   | 38.64  | 108.22 |
| G/S0.5%               | 6.30   | 39.50  | 110.64 |
| G/S1%                 | 7.22   | 45.22  | 126.64 |
| G/S1.5%               | 7.53   | 47.17  | 132.11 |
| B/S0%                 | 4.71   | 29.49  | 82.60  |
| B/S0.5%               | 4.96   | 31.09  | 87.06  |
| B/S1%                 | 5.14   | 32.22  | 90.25  |
| B/S1.5%               | 5.32   | 33.35  | 93.42  |
| E/S0%                 | 2.95   | 18.50  | 51.80  |
| E/S0.5%               | 3.21   | 20.12  | 56.34  |
| E/S1%                 | 3.85   | 24.10  | 67.49  |
| E/S1.5%               | 4.02   | 25.22  | 70.63  |
| G/S0% Numerical       | 9.95   | 59.43  | 109.66 |
| G/S0.5%               | 10.01  | 59.59  | 111.62 |
| G/S1%                 | 10.25  | 61.14  | 113.05 |
| G/S1.5%               | 10.31  | 61.34  | 114.65 |
| B/S0%                 | 7.83   | 46.43  | 81.09  |
| B/S0.5%               | 8.89   | 52.56  | 91.50  |
| B/S1%                 | 9.10   | 53.82  | 91.84  |
| E/S0%                 | 2.95   | 18.43  | 51.96  |
| E/S0.5%               | 3.51   | 21.96  | 61.91  |
| E/S1%                 | 3.84   | 24.01  | 67.69  |
| E/S1.5%               | 4.07   | 25.13  | 70.85  |
| G/S0% Experimental    | 4.00   | 38.00  | 102.00 |
| G/S0.5%               | 7.00   | 30.00  | 115.00 |
Table 3. (Continued.)

| Materials | Methodology | MODE 1 | MODE 2 | MODE 3 | MODE 1 | MODE 2 | MODE 3 | MODE 1 | MODE 2 | MODE 3 |
|-----------|-------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| \(\text{G/S 1\%}\) | \(\text{G/S 1.5\%}\) | \(\text{B/S 0\%}\) | \(\text{B/S 0.5\%}\) | \(\text{B/S 1\%}\) | \(\text{B/S 1.5\%}\) | \(\text{E/S 0\%}\) | \(\text{E/S 0.5\%}\) | \(\text{E/S 1\%}\) | \(\text{E/S 1.5\%}\) |
| 4.00 | 5.00 | 2.00 | 3.00 | 3.00 | 4.00 | 4.00 | 3.00 | 3.00 | 5.00 |
| 48.00 | 45.00 | 28.00 | 32.00 | 34.00 | 36.00 | 22.00 | 25.00 | 28.00 | 30.00 |
| 122.00 | 125.00 | 78.00 | 85.00 | 89.00 | 95.00 | 52.00 | 58.00 | 65.00 | 75.00 |
| 14.00 | 18.00 | 11.00 | 12.00 | 13.00 | 15.00 | 10.00 | 12.00 | 12.00 | 18.00 |
| 65.00 | 85.00 | 60.00 | 53.00 | 52.00 | 53.00 | 35.00 | 46.00 | 48.00 | 52.00 |
| 180.00 | 200.00 | 125.00 | 130.00 | 135.00 | 140.00 | 80.00 | 100.00 | 102.00 | 104.00 |
| 42.00 | 44.00 | 30.00 | 30.00 | 32.00 | 34.00 | 25.00 | 28.00 | 28.00 | 26.00 |
| 112.00 | 112.00 | 70.00 | 79.00 | 80.00 | 86.00 | 76.00 | 90.00 | 92.00 | 90.00 |
| 450.00 | 462.00 | 308.00 | 400.00 | 450.00 | 462.00 | 175.00 | 180.00 | 200.00 | 250.00 |
damping factor values, as those of epoxy nanocomposites, which assess the ability of BFRP nanocomposites for vibration isolation applications. Higher damping factor values of BFRP nanocomposites compared to GFRP nanocomposites, assess the better structural stability of the former for dynamic loading conditions.

5.2. Effect of nanoparticles addition on HDT and hardness of epoxy and FRP composites

HDT is an essential thermal property that measures the effect of temperature on bending stiffness of polymers and composites while applying the load [51]. Two specimens were tested in each case and the average values and their standard deviations are presented in table 4. It is noted from table 4 that the increase in HDT was 19.52%,

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**Figure 9.** Damping factor values of epoxy, GFRP, BFRP and their nanocomposites for one end fixed condition.

**Figure 10.** Damping factor values of epoxy, GFRP, BFRP and their nanocomposites for simply supported case.
54.85% and 84.78%, as the nanoparticles content increase from 0 to 1.5 wt% in epoxy, basalt/epoxy and glass/epoxy composites, respectively, which confirm the dynamic role of nanoparticles on thermal properties of epoxy and FRPC. It is also clear that 1.5 wt% SiO₂/BFRP was relatively higher than 334.32% and 54.56% those of epoxy and GFRP nanocomposites of the same 1.5 wt%, respectively, though both pristine BFRP and GFRP exhibit almost similar HDT. The superior thermal stability of BFRP nanocomposites over the other nanocomposite materials considered in this study is recommended for high-temperature applications.

The hardness values for the above-discussed materials were also given in Table 4. Hardness values were found to be higher at higher nanoparticle loading. In particular, 1.5 wt% silica particles filled basalt/epoxy nanocomposites exhibited higher hardness value while the neat epoxy exhibited lower value among the other combinations.

5.3. X-ray diffraction (XRD) analysis
The XRD patterns of the pristine nano-silica, epoxy, GFRP, BFRP and 1.5 wt% percentage of silica nanoparticles filled epoxy and FRP composites are shown in Figure 12. The broad peak for these material combinations is around 17.4° to 23.5°. These curves reveal the amorphous nature of the epoxy and silica nanoparticles. The combined structure of nano-silica and epoxy in nanocomposites curves in Figure 12 indicate the grafting of silica particles in the epoxy resin is uniform.
6. Conclusions

In the present work, the effect of silica nanoparticles addition on vibration, HDT and hardness characteristics of epoxy, BFRP and GFRP composites were studied. The dispersion of nanoparticles in epoxy and FRP composites was investigated and found uniform dispersion, before performing the tests. The natural frequency values for the first three modes of vibration were investigated experimentally, analytically and numerically with different end conditions such as cantilever, simply supported and fixed-fixed, and obtained close values between the experiments and predictions. The natural frequency values were higher for fixed-fixed end condition whereas higher damping factor values were observed for the simply supported case. In particular, higher natural frequency values were obtained in the third mode at fixed-fixed end condition compared to other boundary conditions and other modes of vibration of GFRP nanocomposites. The magnitude of natural frequency values was higher for GFRP nanocomposites of 1.5 wt% while damping factor (ξ) values were lower for pristine GFRP compared to other material combinations. BFRP and its nanocomposites have higher damping values compared to GFRP and its nanocomposites.

The increase in natural frequency and damping factor values with the increase in nanoparticle content from 0 to 1.5 wt% were observed in epoxy and FRPC. A significant enhancement in HDT and hardness values with the inclusion of nanoparticles in epoxy and FRPC were also observed. In particular, 1.5 wt% nanoparticles filled BFRP composites exhibit higher HDT and hardness values whereas neat epoxy possesses lower values among the other combinations. It assesses the advantage of adding the lower amount of silica nanoparticles (only up to 1.5 wt%) in epoxy and composites. The XRD patterns of nanocomposites indicate that the grafting of nano-silica in the epoxy is uniform. The numerical simulations performed in this study will be highly valuable to composite design society, which could reduce the time and cost in terms of labor, material and instruments. The data presented in this study will be useful to GVT, most importantly, BFRP and its nanocomposites are recommended for vibration isolation and high-temperature applications, owing to their superior damping characteristics and high thermal stability and hardness.
Appendix

Boundary condition: Simply supported
Boundary condition: Cantilever
Boundary condition: Fixed fixed
ORCID iDs

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