Influence of Multiwalled Carbon Nanotubes in the Structural Performance of the Curved Composite Beam

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Abstract. In this paper, Experimental investigation on the free vibration response behavior of multi walled carbon nanotubes (MWCNT) reinforced curved composite beams have been accomplished to evaluate the structural integrity. To obtain the uniform distribution of MWCNTs in the matrix (epoxy), the ultra-sonication technique is carried out and the curved composite beams are fabricated with the incorporation of MWCNT with the curvature radius of 0.8 m then the free vibration analysis is performed at different boundary conditions. The structural performances of the curved composite beams are explored in the relation of modal natural frequencies and damping ratio. The effective structural integrity and vibration responses are achieved with respect to the enhancement of MWCNT in the curved composite structure.

1. Introduction

Composite structures provide better strength, rigidity, and higher stiffness to the low weight ratio and it finds the place in all the industries. Curved composite structures provide a good membrane and bending energy compared to the metallic structures. Therefore it finds the place in the extensive variety of applications especially in automotive, aerospace, marine, astronautics, etc., due to the superior structural and mechanical properties. Numerical exploration on the structural and vibration response of the curved composite beams were performed and it has been reported in literatures. Qatu [1] presented a numerical investigation on the dynamic characteristics analysis of the thin laminated composite shallow curved composite beam based on the Kirchhoff hypothesis and it was clinched that the natural frequencies were improved with increasing the radius of curvature of the curved beam. Ascione and Fraternali [2] developed the one-dimensional curved beam model centred with the Timoshenko beam theory and in the finite element model, the penalty technique was used to solve the numerical problems. Qatu [3] performed the theoretical study on the vibration analysis of the thin and thick curved laminated composite beam based on two cases with and without considering the shear deformation. Tseng and Huang [4] examined the in-plane response of the curved composite beam based on the Timoshenko type curved beam theory with the inclusion of rotary inertia and shear distortion effects for the different curvature and good agreement of results were observed with the analytical solution. The influence of open-angle, orthotropic ratio, and the stacking sequence was also studied with the dynamic stiffness method.

Hajianmaleki and Qatu [5] investigated the static and free vibration response of the thick deep curved composite beam based on the First Order Shear Deformation Theory (FSDT) kinematics and also they developed the numerical model with the pre-defined software ANSYS for the effectiveness. From the work, they determined that the natural frequencies were reduced with an proliferation in the radius of curvature. In 0º stacking sequence they achieved effective results. Ye et al. [6] extended the procedure of series of solutions for the vibration study of the deep curved beam and the Hamilton principle was
used for deriving the governing differential equation of motion based on the FSDT. The influence of boundary conditions, lamination schemes, material properties, geometric parameters, and geometry dimensions were studied. It was established that the frequencies were reduced with an rise in the orthotropic ratio \(E_1/E_2\) and the angle of rotation. Das and Yilmaz [7] studied the free vibration behavior of the curved composite beam through the experimentation and numerical approach. The numerical model was developed through the ABAQUS software and they found better results at fixed at both end conditions. Wang et al. [8] performed a numerical investigation based on the semi-analytical method with the FSDT kinematics. They performed a parametric investigation on varying material properties and geometry structure (elliptic, parabolic, and hyperbolic case) under different support conditions. They stated that the frequencies were reduced with an intensification in the radius of curvature (R) and the orthotropic ratio \(E_1/E_2\). Guo et al. [9] examined the static and dynamic response of the curved composite beam by using the domain decomposition technique with the Chebyshev orthogonal polynomials. The efficacy of the FEM is evidenced with the good agreement in results with available literature and the pre-defined software ABAQUS. It was shown that the frequencies were reduced with an rise in the included angle whereas it increases with an increase in thickness and clamped at both end condition yields the greater frequency and the clamped free yields the least frequency.

However, to induce the better strength and structural performance, the nanofillers are reinforced to the composite structures where Iijima [10] investigated the potentials of the carbon nanotubes in terms of strength and response, it gains the attention of the researchers to work on this. The dispersion of MWCNT into the polymers illustrates the importance of the vibration and mechanical features of the composite structure. Garg et al. [11] made a study on the dispersion techniques of MWCNT and they achieved better results when it was dispersed with the solvent at the 0.3 wt. % of MWCNT in the composite structure. Ayatollahi et al. [12] experimentally presented the impact of aspect ratio \((L/D)\) and wt % of MWCNT in the composite structure and they showed that the MWCNT with lesser diameter provides the better strength at the 0.3 wt. % of MWCNT in the composite structure. Ataollahi et al. [13] addressed the mechanical properties of the laminated composite structure with various wt % of CNT and a 28.3 % increment in flexural modulus was noticed with 0.3 wt. % of CNT content. Khan et al. [14] experimentally evaluated the damping of the laminated composite beam and they achieved an increase in damping to the CNT content at all the modes and the better results were obtained at 1 wt. % of the CNT. Magheshwaran and Ramamoorthy [15] presented the structural analysis of composite shell panels on the free vibration mode and they performed the modal analysis on the completely free environment condition. However, from the detailed report, it was evidenced that the experimentation on the vibration response of the MWCNT embedded curved beam was not yet been reconnoitered on different support conditions.

In this work, the structural performance of the MWCNT reinforced curved composite beams are examined with the experimentation on free vibration. The ultra-sonication technique is carried out to achieve proper dispersion and the curved composite beams are fabricated with and without MWCNT reinforcement then the free vibration analysis is performed at different boundary conditions. The effectiveness of the MWCNT in structural performance is deliberated with the parameters of the modal natural frequencies and damping ratio.

2. Materials and methodology

2.1. Materials

Glass fiber reinforced polymer (GFRP) composite beams were produced with and without MWCNT reinforcement, for sample preparation a separate mold was equipped with the curvature radius \((R)\) of 0.8 m. The uni-axis 220 GSM E-glass fiber, epoxy resin (LY556) and the hardener (HY951) were used for preparing the laminated composite beams. MWCNT with normalized length and diameter of 17 nm and 10 \(\mu\)m is used for this study.
2.2. Fabrication of curved composite beam

Initially, hybrid matrix was prepared. In that process, MWCNT was mixed with the epoxy through the ultra-sonic liquid processor for the proper distribution of the MWCNT in the epoxy and the 1 wt. % of the MWCNT has been used for this study. The conventional hand layup approach with the vacuum bagging setup was adopted to fabricate the curved composite beam. Initially, the curved mold with the curvature radius of 0.8 m was fabricated intended to sample preparation and over the mold, the liberating agent was applied for easy removal of the fiber reinforced composite beam then the fiber was positioned over the mold with the specified fiber angle orientations for the laminated composite beam then further the matrix was applied where the epoxy and the hardener was used in the proportion of 10:1 to achieve the better curing rate of the laminated composites. After that it was kept in the vacuum bagging process for 2 hours then it was allowed to cure at the normal environment condition for one day. Curved composite beam specimens were also fabricated with the infusion of nanofillers (MWCNT). Cross ply (0°/90°/0°/90°/0°) five layered curved composite samples were fabricated with the same weight and volume fraction of fiber and the curved beam images were presented in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Curved laminated composite beam samples with and without MWCNT reinforcement.

2.3. Experimental setup for the structural analysis

Experimentations were made on the simply supported and completely free boundary condition where the experimental setup image is shown in Figure 2 for perspective understanding. The uni-axis accelerometer was placed on top surface of the specimen to collect the transverse signals and the impulse hammer was used to excite the specimens through the roving hammer technique at equal intervals then the transverse vibration responses were composed through the accelerometer from that the voltage signals were rehabilitated into frequency response function (FRF) responses over the data acquisition system and with the assist of pre-defined software Dewesoft 7.1.1. from the FRF the respective modal frequencies and modal damping ratio of the curved composite beam were evaluated. For the investigation, the samples were retained with the geometric measurements of 300 × 50 mm².

![Figure 2](image2.png)

**Figure 2.** Experimental setup for the free vibration analysis of the curved composite beam.
3. Results and discussions

3.1. Structural examination of the GFRP curved composite beam with MWCNT infusion at simply supported (S-S) boundary Condition

The vibration behavior of the curved composite beam was studied at the simply supported (S-S) boundary conditions and this boundary condition was reported based on the real-time practical usage of applications in the surrounding environment. Experimentation on this boundary condition was performed and the corresponding first three modal natural frequencies and damping ratio are shown in Table 1.

| Modes | Natural frequencies (Hz) | Damping ratio |
|-------|--------------------------|---------------|
|       | Without MWCNT | With MWCNT | Without MWCNT | With MWCNT |
| 1     | 14           | 16           | 0.088        | 0.107     |
| 2     | 63           | 72           | 0.045        | 0.063     |
| 3     | 130          | 156          | 0.005        | 0.008     |

From Table 1 it can be noticed that the modal natural frequencies and modal damping ratio were improved at all the modes concerning to MWCNT infusion. The modal natural frequencies of the curved composite beams were enhanced with greater than 10% on the incorporation of MWCNT and also the damping was improved more than 20% in contrast to the GFRP curved composite beam. The enhancement in the structural response was due to the proper bonding between the MWCNTs, matrix, and fiber interfaces also the load transfer capability behavior was enhanced with MWCNTs.

3.2. Structural examination of the GFRP curved composite beam with MWCNT infusion at completely free (F-F) boundary Condition

In hybrid matrix preparation, the vibration behavior of the curved composite beam was also studied under the completely free (F-F) boundary conditions and the structural response are presented in Table 2. The increase in natural frequencies and damping ratio was observed by concerning the MWCNT reinforcement on the curved laminated composite beam.

| Modes | Natural frequencies (Hz) | Damping ratio |
|-------|--------------------------|---------------|
|       | Without MWCNT | With MWCNT | Without MWCNT | With MWCNT |
| 1     | 32           | 40           | 0.03         | 0.035     |
| 2     | 97           | 110          | 0.01         | 0.014     |
| 3     | 177          | 205          | 0.004        | 0.006     |

In completely free environment conditions the sample was not constrained on the edges, so superior natural frequencies are attained in comparison with the simply supported condition where a similar trend was observed in ref [9]. In this condition also the same variation in structural response was observed as like simply supported condition. In completely free condition, the modal natural
frequencies were more but the modal damping ratio is less while compare to simply supported condition due to the constrained environment.

From the discussions, it would be stated that the modal structural response of the GFRP curved laminated composite beam is enhanced at all the modes in-order of reinforcement of the MWCNT on irrespective to the boundary conditions due to the stick-slip mechanism of MWCNTs with epoxy.

4. Conclusions

Vibration behavior of the GFRP curved beam with and without MWCNT reinforcement was studied experimentally to explore the structural response. MWCNT were dispersed with the matrix through the ultra-sonication technique for the proper dispersion rate. Curved composite beams were fabricated with the infusion of MWCNT at the curvature radius (R) of 0.8 m. The free vibration analysis was accomplished at the simply supported (S-S) and completely free (F-F) boundary conditions. Better natural frequencies were obtained at the completely free boundary condition. The modal natural frequencies and modal damping ratio of the MWCNT reinforced curved composite beams were enhanced with more than 10 and 20 % at all boundary conditions. The effective stiffness and damping ratio were achieved to the enhancement of MWCNT in the curved composite structure.

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