Abstract

The present thesis investigates the mechanical and structural behavior of carbon nanotube (CNT)-coated carbon fiber-reinforced (CCCFR) hybrid composites using a novel multiscale modeling framework coupled with finite element analysis. The hybrid CCCFR composites, designed by integrating/coating CNT reinforcements with conventional carbon fibers, aim to overcome the inherent transverse weakness and interfacial limitations of traditional fiber-reinforced composites. The study systematically explores how material processing factors, environmental conditions, and multi-structural parameters influence the stiffness, deformation, and vibration performance of the hybrid composites, providing both fundamental understanding and practical design insights for advanced engineering applications.

The analysis is performed by developing an integrated multiscale approach that couples numerical and empirical techniques across multiple length scales. At the nanoscale, an extended Maxwell-based micromechanical formulation is employed to model the integrated CNT-fiber (ICF) system, incorporating the effect of the interphase layer between the CNT and matrix. The mechanical properties of this ICF are further utilized through a modified mean-field theory (MFT) that accounts for CNT dispersion, agglomeration, and hygrothermal degradation at the microscale level. The three-phase mechanics-of-materials (MOM) model is then used at the mesoscale to capture the collective behavior of the matrix, carbon fiber, and the CNT-coated interfacial layer (CCL), providing homogenized stiffness parameters for the composite lamina. These effective properties are subsequently integrated into a finite element model to predict the plate-level stiffness, deflection, and vibration characteristics of hybrid laminates under different loading and boundary conditions.

Thus, the key novelty of the present work lies in integrating material processing, structural, and environmental effects within a unified modeling scheme, which has often been overlooked in prior studies. The study incorporates the influence of CNT aggregation, interphase thickness, and hygrothermal variations on mechanical performance, revealing their coupled impact on static and dynamic response. It is shown that increasing CNT content enhances stiffness and natural frequencies up to an optimal threshold, beyond which excessive agglomeration or softening of the interphase and matrix under hygrothermal conditions reduces the benefits. Smaller CNT diameters, moderate interphase thickness, and uniform dispersion significantly improve stress transfer efficiency, while temperature and moisture lead to matrix softening and interfacial weakening, reducing static and dynamic performance. A detailed parametric study also reveals that effective optimization of nanoscale to mesoscale parameters can achieve superior structural rigidity and improved dynamic characteristics. Overall, the thesis establishes a unified top-down localization and bottom-up homogenization multiscale framework that captures the interconnection between nanoscale reinforcements and global mechanical behavior, providing valuable guidelines for the design of lightweight, multifunctional, and durable hybrid composite structures for aerospace and high-performance structural applications.

Keywords: Hybrid composite; Carbon nanotube (CNT); Finite element method (FEM); Agglomeration; Interphase; Hygrothermal; Multiscale model; Free-vibration; CNT-waviness; First order shear deformation theory (FSDT); Mechanics of material (MoM) method, Mean-field theory; Maxwell theory.