Abstract

Fiber-reinforced composites (FRC) are widely used in aerospace, defense, automobile, and railway applications because of their improved mechanical properties, lower weight, and efficient impact absorption energy. The advantage of composite material is that it has higher specific strength and specific stiffness (modulus) compared to most of the industrially used metals. The mechanical properties of composites are defined in terms of modulus and strength. The strength is further defined by static and fatigue strength. The current design practice in industry uses failure criteria to design composite structures. In the failure criteria, static strength is utilized. Fatigue of composite structures is also a critical aspect in the field of materials engineering, particularly in industries such as aerospace where weight is an important parameter. Fatigue in composite structures manifests through mechanisms such as matrix cracking, fiber-matrix debonding, delamination, and fiber breakage, which can propagate progressively, leading to catastrophic failure if not addressed effectively. The objective of research work is to address the prediction of static and fatigue properties of unidirectional (UD) and multidirectional (MD) composite material using developed analytical and machine learning models. These properties would be useful in the initial design phase of aircraft structure for the composite materials whose static and fatigue properties are not available and characterization is to be done. The research work begins with the development of predictive models for ultimate tensile strength using experimental data. Multiple Linear Regression (MLR) and Artificial Neural Networks (ANN) are employed to capture the relationships between material parameters and composite strength. The study is then extended to fatigue life prediction using the estimated static strength, incorporating a progressive strength degradation (PSD) approach. The PSD model is validated through both finite element (FE) simulations and experimental data, followed by fatigue life estimation using a modified Basquin equation for different composite laminates. The proposed modified Basquin equation predicts fatigue life of Multi- directional composite laminates using the static strength generated by the PSD method. To enhance fatigue prediction capabilities, a strain energy-based method is proposed, initially validated on metallic alloys and subsequently applied to UD glass-epoxy and carbon-epoxy laminates. This approach considers the elasto-plastic behaviour of matrix (epoxy) based composites, culminating in a novel strain energy- based fatigue life prediction model tailored for composite materials. Further, the thesis presents a statistical framework for fatigue life prediction from experimental data. Utilizing the Stussi function for S-N curve generation, the model integrates variability through the coefficient of variation (CoV) and employs probabilistic methods to estimate fatigue life at various confidence levels.

An experimental investigation was conducted on bidirectional glass–epoxy composite laminates to evaluate their static and fatigue performance. Tensile tests following ASTM standards were carried out to determine ultimate strength, while tension–tension fatigue tests were performed to generate S–N behaviour. The measured static strength showed excellent agreement with predictions from the progressive strength degradation method, and the experimentally obtained fatigue life closely matched the modified Basquin-based analytical fatigue model. The strong correlation between experimental and analytical results validates the reliability of the proposed modelling framework for assessing both static and fatigue behaviour of bidirectional glass–epoxy laminates.

Collectively, this research advances the understanding of composite fatigue behavior and offers practical tools for more reliable and cost-effective design of composite structures considering fatigue aspects. The methodologies developed here have the potential to support damage-tolerant design practices, reduce maintenance costs, and extend the service life of critical structural components in high-performance engineering applications.

Keywords: Fiber-Reinforced Composites, Ultimate Tensile Strength, Fatigue Life Prediction, Machine Learning, Artificial Neural Networks (ANN), Progressive Strength Degradation(PSD), Strain Energy Method, Statistical Modeling,S-N Curve