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Physics-Based Intelligence for Structural Optimization in Next-Generation Aerospace Composites

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Abstract

We present an integrated design framework for multi-zone optimization of aerospace-grade carbon fiber reinforced polymer (CFRP) components, combining high-fidelity finite element simulations with physics-informed machine learning (ML) models. The approach addresses the current limitations of composite laminate design, namely, the dependence on expert-driven iterative processes, high computational costs, and the incompatibility of black-box models with aerospace certification requirements. The framework builds on a database generated from flexural simulations and experimental validation of CFRP coupons under various loading modes. This dataset links stacking sequences to mechanical response and failure indices, enabling the training of predictive surrogate models. These models are used to explore the design space efficiently and identify high-performance laminates while incorporating physical constraints and manufacturability criteria. SHAP based explainability is embedded to quantify the contribution of each lamination parameter, ensuring traceability and model transparency in line with aerospace standards. The framework is demonstrated on a stiffened beam representative of secondary aircraft structures, optimized under multiple load cases to minimize mass while meeting buckling, stiffness, and failure constraints.

Lamination parameters are optimized in a continuous design space and reconstructed into manufacturable stacking sequences that satisfy symmetry, balance, and blending rules. The final design achieves a 10–15% mass reduction compared to a baseline configuration, with preserved structural margins and fabrication feasibility. This work illustrates how data driven approaches can be reconciled with certification driven design workflows, enabling the transition to fully digital, traceable, and efficient composite structure development. The proposed framework supports the adoption of real-time, optimization guided engineering in aerospace composite design.

Keywords:

Carbon Fiber Composites Laminate Optimization Physics-Informed Machine Learning SHAP Aerospace Structures.