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A Data-Driven Framework for Multiscale Prediction of Crack Paths in Carbon fiber–reinforced composites

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Extended Abstract

Abstract

Introduction：Carbon fiber–reinforced composites (CFRCs) have been widely applied due to their superior mechanical properties and high strength-to-weight ratio. Under transverse or complex coupled loading conditions, intralaminar matrix cracking is the first damage mode to occur and significantly affects structural stiffness and fatigue life. In studying the problem of intralaminar matrix cracking, the anisotropy of the material and the random distribution of fibers at the microscale make it challenging to accurately predict crack propagation paths[1-2]. Research overview：Finite element analysis (FEA) can simulate transverse matrix cracking and crack propagation at the microscale. However, this approach requires considerable computational resources and time, and its applicability is generally limited to a single scale, restricting its use in practical engineering scenarios[3]. To overcome these limitations, many researchers have explored data-driven approaches to address the low computational efficiency and high cost of FEA[4]. For instance, Gu et al.[5] developed three deep learning models for predicting transverse cracking in glass fiber–reinforced composites. Wang[6] proposed a neural network framework using microstructure and crack modes as inputs to characterize the influence of porosity defects on crack behavior. Although data-driven surrogate models have been widely used for predicting microstructural crack patterns and propagation paths in composites, most methods remain confined to a single scale. Consequently, extending microscale predictions to macroscale matrix cracking remains difficult, leading to insufficient understanding of the continuous evolution of complete crack paths and limiting their practical applicability. Method：To address this challenge, the present study proposes a two-step deep learning framework for multiscale crack path prediction in CFRCs, trained on datasets generated by a phase-field model. In the first step, the microscale model uses two-dimensional geometries with varied fiber distributions under tensile loading as input and phase-field crack paths as supervision. The encoder–decoder network employs a ResNet encoder for feature learning and a U-Net decoder with attention and atrous spatial pyramid pooling to capture multiscale context and long-range interactions. The loss function includes physics-informed constraints that penalize nonphysical crack–fiber overlap and account for inter-fiber spacing effects, enhancing the physical realism of predictions. To achieve scalability, the predicted crack endpoint on the right boundary of one geometry serves as the initial crack on the left boundary of the next. In the second step, transfer learning on geometries with random fiber distributions and diverse initial cracks enables accurate inference, ensuring crack continuity across microregions and supporting large-scale path prediction through local model stitching. Results & discussion：Comparative analysis between prediction and phase-field simulations for typical single-layer structures demonstrates that the proposed method achieves excellent performance, enabling continuous and accurate prediction of intralaminar matrix crack paths at larger scales based on microscale models. The proposed two-step data-driven approach substantially reduces computational cost and time while achieving accurate multiscale crack path prediction. This method provides a promising framework for extending microscale surrogate models to macroscale applications and demonstrates strong potential for practical use in multiscale crack prediction.

Keywords:

data Driven crack path prediction phase field