

Machine learning-based uncertainty quantification of failure predictions

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Introduction

Composite materials are extensively used in civil aircraft due to their ability to create lightweight, strong structures and enable innovative structural designs. However, their complex failure mechanisms, which are highly sensitive to loading conditions and microstructural features, pose significant challenges. This uncertainty, reflected in material properties, necessitates accounting for uncertainties in the design of composite structures.

To optimize performance and ensure safety, it is crucial to address these uncertainties during the early design stages. This requires efficient failure prediction and uncertainty quantification (UQ) to establish accurate safety margins. UQ also helps pinpoint critical areas that could compromise structural integrity, enabling proactive maintenance and reducing the risk of in-service failures.

This study uses an innovative Z-beam wing box concept [1], designed for the wing tip region of high aspect ratio wings to enhance bend-twist coupling, as a case study. A novel, fast uncertainty quantification method for failure prediction is proposed, tailored for the preliminary design of large composite structures. Machine learning models are employed to predict failure hotspots and indices across various wing box geometries (as shown in Figure 1) and layups. The method integrates uncertainties in fiber orientations to quantify prediction uncertainty.

Training data for these machine learning models is derived from multiscale simulations, illustrated in Figure 2. At the structural element level, strain states are applied using periodic boundary conditions, and displacement boundaries around failure hotspots are identified. At the hotspot level, stress fields are analyzed on a refined mesh through a global-local approach. Failure indices (FIs) are then calculated using a suitable failure model [2-3]. By evaluating various strain states, a failure index map is generated to identify maximum FI values, from which the failure envelope is derived.

Using data from wing boxes with diverse geometries and layups, the proposed fast UQ method is trained, as shown in Figure 3. The method inputs geometric parameters (Θ) and ply percentages of different orientations (Ω) into a machine learning model. To account for fiber orientation variability (Γ) under the same Ω , a technology factor (κ) is introduced, modeled as a Gaussian distribution. Bayesian neural networks are used to capture uncertainties in stress field predictions. Uncertainty propagation is then conducted via linear error propagation. This approach provides the expected value and variance of FIs under different strain states, aiding preliminary design efforts.

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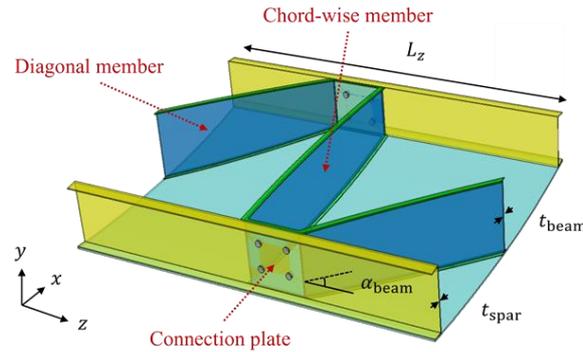


Figure 1: Geometric parameters of the Z-beam wing box element

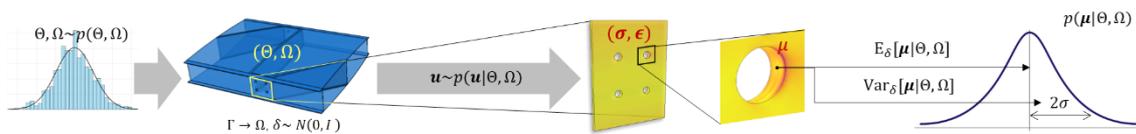


Figure 2: Process of the multi-scale simulation and uncertainty quantification of composite Z-beam wing box elements.

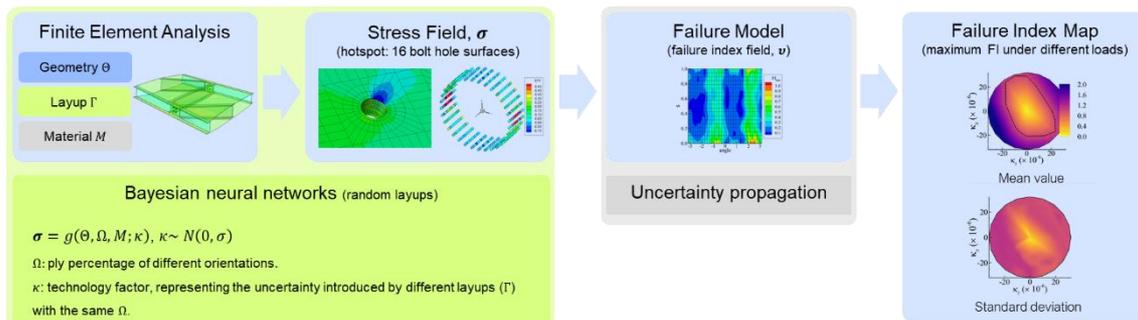


Figure 3: Architecture of the proposed machine learning-based uncertainty quantification method

References

- [1] L. Iorga. Aerofoil structures with stiffness properties adjustment component. U.S. Patent No. 11,772,780 B2. United States Patent and Trademark Office. 3 Oct. 2023
- [2] S. T. Pinho, M. Matos, R.O.S.S. Costa, A. Ibbotson, M. Ostergaard. Enabling multiscale analysis of very large composite structures. COMPOSITES 2021, 22-24 September 2021, Göteborg, Sweden.
- [3] S. T. Pinho, R Darvizeh, P Robinson, C Schuecker, and PP Camanho. Material and structural response of polymer-matrix fibre-reinforced composites. Journal of Composite Materials, 46(19-20):2313–2341, 2012.