Thesis: Refined structural modeling for progressive damage and fatigue analysis of composite structures

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Abstract

The increasing use of composite materials in aerospace and mechanical structures has led to a growing demand for reliable numerical tools capable of predicting damage initiation, damage evolution, and fatigue life under realistic service conditions. Unlike metallic materials, composite laminates exhibit complex failure mechanisms governed by material anisotropy, multi-axial stress states, and the interaction of multiple damage modes, such as fiber breakage, matrix cracking, and shear-driven failure. These challenges are further amplified when structures are subjected to variable-amplitude and stochastic loadings, where fatigue damage accumulates over a large number of cycles and is strongly influenced by the spectral content of the excitation.

From a modelling perspective, the accurate prediction of damage and fatigue in composite structures requires the reliable reconstruction of the three-dimensional stress state, including interlaminar and shear components that are often neglected or poorly approximated by classical low-order theories. At the same time, full three-dimensional solid-element models, while accurate, remain computationally prohibitive for large-scale structures and parametric analyses. The trade-off between accuracy and efficiency represents one of the central challenges addressed in the present research activity.

Within this context, the objective of this thesis is to develop and validate a numerical framework capable of accurately predicting progressive damage under quasi-static loading and fatigue response in metallic and composite structures, while maintaining a reduced computational cost. The research is conducted within the framework of the Carrera Unified Formulation (CUF), which provides a systematic and hierarchical approach for the development of refined beam and shell theories. CUF enables the construction of structural theories capable of reproducing three-dimensional stress states by adopting advanced kinematic descriptions.

The research activity is structured into two research lines. First, the focus is placed on the progressive damage analysis of composite laminates under quasi-static loading conditions. A continuum damage mechanics framework is adopted and extended through the implementation of three-dimensional failure criteria. The Hashin 3D formulation is employed to model tensile-dominated damage mechanisms, while a combined Hashin-Puck criterion is introduced to improve the description of compressive and matrix-dominated failure. The damage models are embedded within CUF-based layer-wise finite element formulations, allowing damage initiation and evolution to be investigated at the ply level. Numerical simulations are performed on a variety of benchmark specimens, including notched and open-hole configurations, demonstrating that the proposed approach is able to accurately reproduce experimental responses and reference numerical solutions while maintaining computational efficiency.

The second line of the thesis addresses fatigue life estimation under stochastic loading using frequency-domain methodologies. The structural response to random excitations is characterized through stress power spectral densities obtained from CUF-based simulations. Fatigue damage is then evaluated without an explicit time-domain integration by adopting spectral fatigue methods, with particular emphasis on the Dirlik formulation for stress-range probability density estimation. For metallic structures, the frequency-domain framework is coupled with linear elastic fracture mechanics, enabling crack-growth prediction through equivalent stress intensity factor ranges derived from spectral stress information. For composite structures, the frequency-domain approach is extended by introducing an equivalent stress definition based on the Tsai-Hill failure criterion, allowing fatigue life estimation while accounting for material anisotropy and multi-axial stress states. The results show that fatigue damage cannot be predicted solely from global quantities such as the stress root mean square. A proper fatigue assessment requires the full stress-range probability density function, which in turn depends on an accurate three-dimensional stress reconstruction.

The proposed framework is validated through numerical applications involving both broadband excitations defined by constant power spectral densities and physically based stochastic loading conditions derived from the von Kármán turbulence model. The results highlight the strong interaction between the load spectral content, structural dynamics, and fatigue damage accumulation, as well as the significant influence of laminate stacking sequence on fatigue performance and sensitivity to stochastic loading parameters.

Overall, this thesis demonstrates that CUF-based higher-order structural models provide a quantitatively improved balance between accuracy and computational efficiency for the analysis of progressive damage and fatigue in metallic and composite structures. In progressive damage analyses, increasing the order of the structural theory leads to a clear improvement in agreement with experimental results. For instance, in the center-notched tensile test, higher-order CUF models predict equivalent stresses at damage initiation within the experimental scatter band, whereas low-order formulations exhibit larger deviations. The results further show that mesh refinement alone is insufficient to ensure accuracy, highlighting the dominant role of the adopted structural theory. At the same time, CUF models are shown to be less sensitive to specimen size in terms of computational cost, as accurate predictions can be obtained using coarser meshes combined with higher-order through-the-thickness kinematics. For compact tension and compressive tests, CUF formulations coupled with advanced damage models provide force–displacement responses in good agreement with experiments. In particular, Hashin-based CUF models predict damage initiation with errors below 10 % for peak force if compared with experimental results. Discrepancies observed in low-order models are mainly attributed to the absence of delamination modeling, while higher-order CUF approaches are shown to better capture damage localization and initiation trends. In the context of fatigue life estimation under stochastic loading, quantitative comparisons highlight the importance of three-dimensional stress reconstruction. CUF-based two-dimensional models provide an effective framework for fatigue life prediction across different levels of kinematic refinement. Higher-order CUF formulations, while more computationally demanding than low-order models, enable accurate fatigue life predictions and a reliable reproduction of three-dimensional stress fields when compared with full 3D FEM analyses. Low-order CUF models, instead, are primarily employed in this work for extensive parametric analyses, where computational efficiency is essential and the focus is on capturing global trends and sensitivities.