Abstract

The applications of composite materials and structures have recently risen due to their exceptional mechanical properties and multifunctional capabilities. Nevertheless, a thorough analysis of their failure mechanisms, particularly under complex loading conditions, remains a significant challenge. Fatigue, as the most common failure mode in real-world structures, encompasses these complex conditions and continues to be a focal point of research. Precise estimation of fatigue life is essential for the design and maintenance of mechanical systems and structures, as it determines the maximum loading cycles a material can endure before failure. The primary aim of this thesis is to study fatigue and fracture of composite structures. Conventional methods addressing this issue often suffer from being time-consuming, lacking universality, or exhibiting reliability concerns. This thesis introduces innovative criteria based on Finite Fracture Mechanics to first analyze debonding failure and then address fatigue failure in composite structures. Additionally, a fatigue analysis leveraging the powerful numerical approach of Phase Field is conducted.

Focusing on composite structures, debonding emerges as a fundamental failure mode influencing the structure's ultimate load-bearing capacity. As a starting point, FFM is employed to analyze debonding behavior in composite structures, specifically in the direct shear test – a pivotal test for understanding debonding in externally bonded systems. A comparison with the cohesive zone models enriches this analysis. Given the presence of geometric discontinuities such as cracks, notches, and holes in mechanical components – whether by design or due to external factors – it is crucial to analyze their role as stress concentrators, affecting the structural durability and functionality. Subsequently, FFM is developed by the author to estimate the finite fatigue life of notched elements in isotropic materials, for the first time. The next step extends the model to assess the fatigue lifetime of notched laminated composites. With a comprehensive experimental campaign on notched carbon fiber laminated composites, validation is performed. Finally, the Phase Field model, having been recently adapted for fatigue, is examined and validated through experimental data to derive the Paris curve, based on available experimental data in the literature.

Regarding the outcomes, for analyzing the debonding in composite materials using direct shear tests, closed-form solutions are proposed to fully study the effect of different parameters. The results highlight the importance of considering residual strength (friction) in the analysis even at debonding onset. The models demonstrate high accuracy in predicting the failure load in experimental data, based on the interface mechanical properties obtained from a single test. Furthermore, to extend FFM to the finite fatigue life regime, the effectiveness of the methodology is first confirmed through various experimental data encompassing a wide range of notch geometries (such as circular holes, U- and V-notches), loading scenarios (including tension and bending), load ratios, and materials (like steel, aluminum, and samples produced through additive manufacturing). Due to the low computational cost of the model, parametric studies on the effect of notch geometry on fatigue life are performed. Then, without relying on any fitting parameters from experimental data and only employing standard tests, as well as utilizing (semi-analytical) stress and energy fields, the FFM model is employed to study the fatigue lifetime of notched orthotropic plates. Despite the complexity of the problem, high accuracy is achieved, and results demonstrate a consistent behavior with the conventional hole size effect, i.e., the number of cycles to failure for a given stress amplitude decreases as the hole radius increases. Finally, the robustness and reliability of the Phase Field approach as a computational tool for predicting the fatigue failure of structures are proved when its results are compared to experimental data. This research paves the way for more efficient and reliable design and maintenance protocols in aerospace, automotive, and civil engineering industries, where the lifetime and safety of composite structures are paramount.