Methodology for adaptive accelerated fatigue testing of thermoplastic composites considering the self-heating effect

Scientific-popular abstract

Thermoplastic composites reinforced with carbon fiber have become highly relevant to industries, particularly in aviation and aerospace applications. Their unique properties, including high mechanical performance, resistance to heat and impact, low weight, simplified manufacturing, and recyclability, make them a durable, cost-effective, and sustainable alternative to metallic alloys and thermoset composites. Aerospace manufacturers increasingly use them to replace traditional parts such as fuselage shells and torsion boxes for aircraft stabilizers, thereby improving efficiency, safety, and environmental performance in modern aviation.

Despite their superior properties, these materials remain susceptible to mechanical fatigue, requiring detailed investigation, especially given their long service life. Thermoplastics can endure billions of load cycles, but what happens afterward? In practical terms: how will composite aircraft components perform after 30, 40, or even 50 years? How can their fatigue life be predicted and this knowledge used to design structural components that meet sustainability criteria? Finally, how can the fatigue behavior of materials be studied with such long service lives?

The submitted project proposal addresses these questions. Through collaboration between international teams at the University of Freiburg and the Silesian University of Technology, we are developing a methodology to accelerate fatigue testing by applying ultrasonic-frequency loading, reducing test duration from years to weeks. A major challenge at such frequencies is the self-heating effect, generated by the viscoelastic properties of polymers and polymer matrix composites. This effect dominates the material response, accelerates structural degradation, and prevents direct comparison of fatigue results with those obtained at lower frequencies.

To address this challenge, the project team investigates the thermomechanical behavior of thermoplastics during fatigue at low and ultrasonic frequencies, with comprehensive analysis of structural degradation and damage accumulation. Planned fatigue tests in both regimes will identify critical self-heating temperature intervals that can be treated as material properties representing fatigue durability. The project also aims to answer the question of transferring results between loading regimes by developing a model that enables proper interpretation of data obtained under ultrasonic loading. This will support the development of a composite fatigue degradation model that integrates low-, high-, and very-high-cycle fatigue into a single S-N curve, typically used to represent fatigue performance of materials.

Preliminary and collaborative investigations by our international team confirmed the relevance of these studies and produced promising results in this field. Based on the developed model, the project will implement adaptive fatigue testing using fuzzy controllers, enabling final validation of the methodology.

From a practical perspective, the developed methodology greatly accelerates fatigue testing of thermoplastic materials while ensuring reliable results through adaptive control of the self-heating effect, thereby avoiding its undesirable influence. Another outcome is a method to determine critical self-heating temperature intervals, which can serve as a fatigue durability measure and significantly reduce the number of experiments needed to characterize composite fatigue performance and design criteria.