

UNDERSTANDING TEMPERATURE-DEPENDENT FAILURE MECHANISMS IN COMPOSITES: INSIGHTS INTO CRACK INITIATION TEMPERATURE (CIT)

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ABSTRACT

The low-temperature performance of composites has gained increasing interest in recent years due to growing research and development activities in the hydrogen economy. The storage of liquid hydrogen in composite tanks is a particularly promising application in the aviation sector, where lightweight materials with exceptional low-temperature performance are critical [1]. However, the utilization of composites under cryogenic conditions is associated with extreme demands on the temperature and thermal fatigue resistance of the fiber-reinforced materials. Microcracking of the resins and fiber-matrix interphases and micro-delaminations of the plies are typically evolving during extreme low service temperatures [2].

Therefore, the present study introduces the *Crack Initiation Temperature* (CIT) as a reliable metric for evaluating the suitability of materials under low-temperature conditions. The CIT is defined as the temperature at which the first cracks in the matrix or the initial failure of the fibre-matrix interphases occur due to thermal stresses arising while cooling. It serves as a critical parameter for assessing material performance in extreme environments.

A multiscale modelling approach is employed to analyse and compare three composite materials: a reference material based on DGEBA epoxy resin cured with DETDA, a polyurethane-modified variation, and a carbon nanotube (CNT)-modified variation. The composite models incorporate T700 and T800 carbon fibres to reflect typical high-performance applications. Temperature-dependent material properties are represented through mathematical equations, derived from a combination of literature data and experimental results, to accurately capture the behaviour of each material across the full temperature range. Key properties—including stiffness, strength, fracture toughness, and interface parameters—are modelled as functions of temperature to ensure consistency and precision in the simulations.

In the microscale model, a linear elastic epoxy material model is combined with a traction-separation law for the fibre-matrix interphase and a linear elastic model for the fibres. For the mesoscale model, a homogenized material model is utilized for each layer with a predefined layout. The stress states computed in the mesoscale model are transferred to the micro model for further analysis.

According to the literature, polyurethane modification of epoxy reduces the elastic modulus of the matrix and lowers the glass transition temperature (T_g) while significantly increasing the fracture toughness [3]. This increase in fracture toughness is more pronounced at higher temperatures but diminishes at low temperatures [4]. In contrast, CNT-modification has minimal effect on the stiffness of the matrix but significantly enhances the interface strength and the fracture toughness of the resin, with these improvements being particularly notable at low temperatures [5].

As both types of matrix modifications affect characteristic material properties, such as fracture toughness, stiffness, and interphase strength, these effects are incorporated into the simulations. In detail, the consideration allows for an in-depth evaluation of their impact on the CIT. A key objective of this study is to identify the most sensitive material properties affecting the CIT by systematically analysing the temperature-dependent behaviour of the introduced configurations.

Simulations are performed to evaluate thermal stresses and predict the CIT while cooling the materials from 350 K to 20 K. The results highlight the influence of temperature-dependent properties and material modifications on CIT, offering valuable insights for designing cryogenic components. This work demonstrates the potential of CIT as a critical parameter for selecting and optimizing composite materials in extreme low-temperature environments.



Figure 1: Normal stress distribution in the micro model.

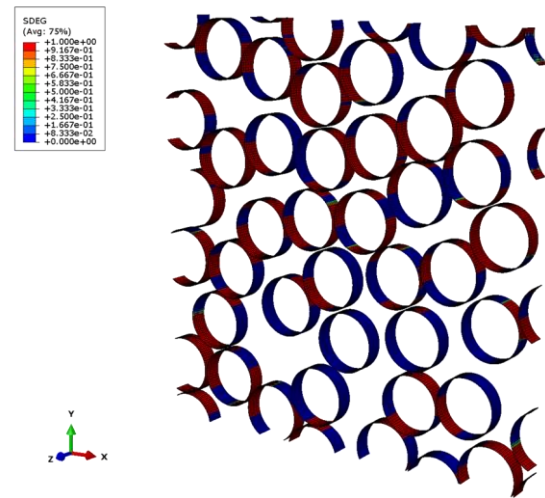


Figure 2: Interface Damage.

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