
Gradient damage model for simulating thermo-mechanical coupling: application to composite material degradation

Mhadji Abdoussalam^{*1}, Azdine Nait- Ali^{†1}, Benjamin Batiot^{‡2}, and Damien Halm^{§1}

¹ENDOmmagement et durabilité [Institut Pprime] – Pprime Institute - UPR CNRS 3346 - ISAE-ENSMA – France

²Combustion hétérogène et milieu poreux [Institut Pprime] – UPR CNRS 3346 - ISAE-ENSMA – Poitiers University, France – France

Abstract

Keywords: composite material, damage, thermal degradation, gradient-based model, crack, coupling, microstructure, interface, pyrolysis, heterogeneity, phase field

The use of composite materials is widespread in structures where weight reduction is essential while maintaining high stiffness and strength properties. However, these materials are flammable, increasing fire risks. It is generally observed that heat flux transforms sound composite material into char, leading to the degradation of mechanical properties and a modification of initial thermal properties. Nevertheless, the influence of microstructural heterogeneity on thermal degradation, as well as the coupling between thermal degradation and mechanical damage, remains underexplored in the literature.

The objective of this study is to investigate the influence of mechanical and thermal degradation mechanisms on physical phenomena such as heat transfer, thermal decomposition, and cracking. The study aims to simulate the interaction between different degradation modes and their kinetics to assess their mutual impact on the material's behavior at the microstructural scale. To achieve this, a rigorous thermodynamic approach is adopted, introducing internal variables corresponding to each physical phenomenon, as well as their gradients.

This modeling approach combines two methods: on the one hand, a phase-field gradient model is employed to describe thermal degradation, which evolves according to an Arrhenius law. This method is suitable for simulating phase transition phenomena and interface motion in a non-homogeneous material. This approach introduces a degradation gradient term to characterize the interface energy between degraded and sound regions, allowing the influence of microstructural fluctuations to be considered.

On the other hand, a gradient damage model based on the principle of virtual powers distinguishes the thermodynamic forces associated with the reversible process, derived from

*Speaker

†Corresponding author: azdine.nait-ali@ensma.fr

‡Corresponding author: benjamin.batiot@univ-poitiers.fr

§Corresponding author: damien.halm@ensma.fr

free energy, from those associated with the irreversible process, derived from the dissipation potential. This modeling choice avoids issues related to damage localization and mesh dependency. By coupling these two approaches, it becomes possible to simulate the interaction between mechanical damage and thermal degradation of the material.

The results show that, on the one hand, charred regions become areas where damage and cracking are easily initiated due to the degradation of mechanical properties. On the other hand, damaged or cracked zones act as thermal barriers, delaying heat propagation. Indeed, the presence of cracks reduces thermal conductivity in these regions, thereby limiting the advancement of the thermal front.