

Experimental/numerical investigation of hygrothermal aging in fiber-reinforced composites

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ABSTRACT

Fiber-reinforced composites have an intrinsically multiscale mechanical behavior. Formulating and calibrating mesoscopic (ply-level) models that accurately account for the underlying microscopic mechanisms that drive macroscopic failure is therefore an arduous task. In particular, predicting mechanical degradation caused by hygrothermal aging (a combination of high temperatures and moisture ingress) is a challenging task for which no comprehensive solution is currently available.

After diffusing into the composite material, moisture interacts with polymer chains and leads to an increase in chain mobility which causes reductions in stiffness and strength (plasticization), changes in volume (swelling) and chemical breakage of polymer chains (hydrolysis). If fibers are present which do not absorb water, differential swelling stresses arise which can lead to resin fracture and fiber/matrix interface debonding. These physical and chemical phenomena acting at the microscale interact nonlinearly and lead to complex macroscopic degradation behavior. Realistic predictions of composite material durability requires microscopic mechanical tests and observation techniques as well as high-fidelity multiscale and multiphysics numerical models.

This work investigates the phenomenon of hygrothermal aging in unidirectional composites through a combination of micro- and macroscopic experiments and multiscale numerical modeling. Composite samples are immersed in hot water for different durations and tested both directly after aging as well as after being redried. The effects of aging on the fiber-matrix interface adhesion are investigated through single-fiber fragmentation tests in dry and saturated specimens and interfacial properties are obtained through reverse modeling. The aging mechanisms responsible for degradation are investigated through a fractographic study on aged specimens using X-ray 3D computed tomography.

To model the influence of microscopic processes on the macroscopic behavior, aging is simulated with a computational homogenization (FE²) approach, which offers a continuous link between scales, precluding the need for macroscopic constitutive assumptions. The multiscale stress model is coupled with a macroscopic diffusion analysis that computes the evolution of the water concentration field. A viscoelastic/viscoplastic/damage model is used to describe the resin at the microscale and cohesive-zone elements with friction are employed at the fiber-matrix interfaces. To reduce the exceedingly high computational cost of the FE² approach, the micromodels are accelerated by a combination of two model-order reduction techniques. The resultant predictions are compared with experimental results.