LIFETIME PREDICTION OF SELF-HEALING CERAMIC-MATRIX COMPOSITES USING A MULTI-PHYSICS IMAGE-BASED MODEL

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We propose a multi-physics numerical model to predict the lifetime of self-healing ceramic-matrix composites (CMC) under mechanical load and oxidative environment. Finite element models of CMC's tow are constructed from micrographs of real materials. A matrix crack perpendicular to the loading direction is considered as the ingress of oxidative species (Fig. 1). The diffusion of oxygen, and its reaction with the boron-rich matrix layers to form a liquid oxide, are simulated using a dedicated finite element framework: the transport phenomena are averaged in the crack height and mass fluxes resulting from the chemical reactions are treated as effective boundary conditions. A thorough analysis of the resulting coupled PDEs allowed us to define characteristic times for each phenomenon and to derive an appropriate time-stepping strategy. In addition, the progressive degradation of the fibers is considered thanks to a slow crack growth model accounting for the evolution of oxygen concentration within the crack. The mechanical equilibrium is established after each fiber break, leading to reloading of the surviving fibers and eventually to the re-opening of the crack. This process is repeated iteratively until a critical fraction of broken fibers cause the catastrophic failure of the tow.

The lifetime of the tow could then be predicted depending of the environmental conditions but also on the fibers' characteristics. Our results show a complex interplay between the fibers' initial strength and their spatial distribution within the tow, which cannot be captured by simpler 1D models. The initial statistical fiber strength distribution is strongly affected by the cumulated oxygen flux experienced by each fiber, depending on its particular location and the healing process. Fibers close to the boundary of the tow experience a larger amount of oxygen and will fail prematurely, regardless of their initial strength. Inversely, the farther fibers survive until the ultimate failure of the tow. Indeed, the lifetime of the tow in mainly dictated by the intermediate fibers.

A large number of simulations were conducted for various numbers of fibers, tow aspect ratios, fibers spatial distribution and environmental conditions to further explore this interplay. These simulations were supported by a variance-based sensitivity analysis that enabled us to identify the main couplings. That eventually leads us to propose an effective scaling law for both size and shape effects, from which we can predict the lifetime distribution of a tow with arbitrary number of fibers and aspect ratio. These predictions compare favorably with direct simulations on real tows geometry.

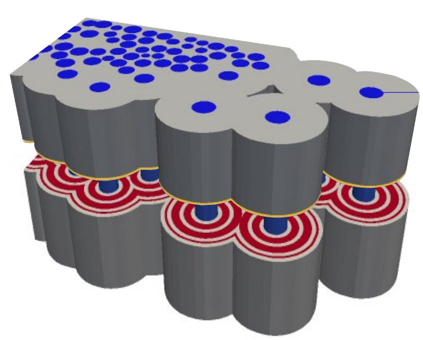

Figure 1 – Schematic view of a CMC tow with a matrix crack