High fidelity computer simulation to predict damage in advanced ceramic composites for nuclear energy

Composite materials, made from ceramic fibres within a ceramic matrix, can have excellent strength and tolerance to damage at very high temperatures. They have been chosen to protect the fuel in some future designs for advanced nuclear reactors, and may be used to replace the metals that currently surround the fuel to produce accident tolerant fuels for current reactor designs.

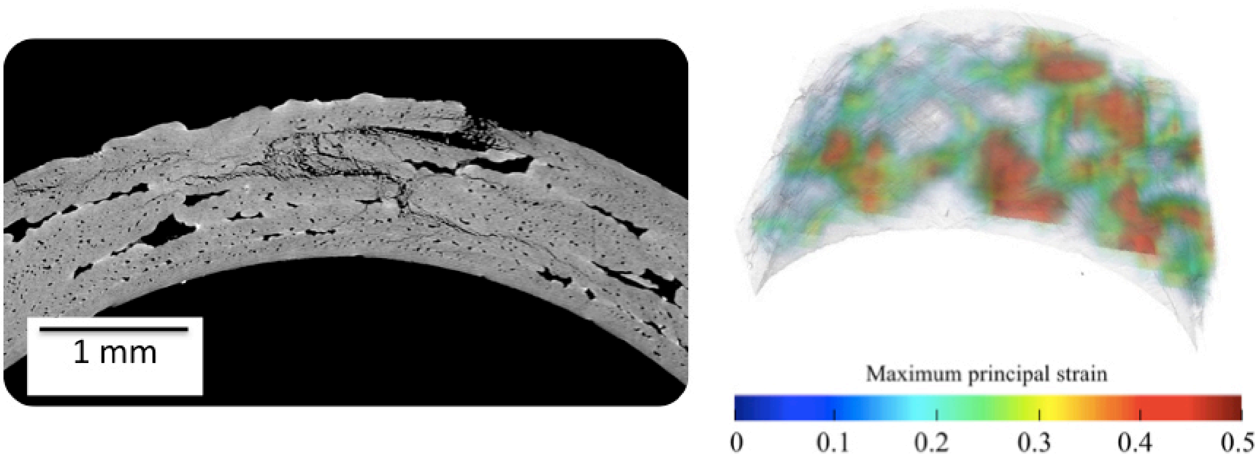

Fig. 1. X-ray computed tomograph of damage in a ceramic composite (left), with the deformation caused by damage shown more clearly as strain, measured by digital volume correlation (right).

The extreme conditions inside nuclear reactors can change the properties of the composite. Tests are done to examine and understand this, to ensure that future behaviour is predictable and also to improve the design and manufacture of these materials. It is impossible to do tests under all feasible conditions, so modelling is used to predict the performance of these composite materials. The models need to consider the complex microstructure of the composite, including the properties of the individual materials and the way that they are arranged. Most composites have complex woven microstructures, and the models need to be able to consider the structure of the weave and possible defects in the weave, how the composite will behave under complex types of loading, and also the many possible variations in this.

This can be done using numerical modelling, which is an approach widely used in industrial component design in civil, automobile, aerospace and nuclear engineering. However, current numerical modelling methods that can simulate the interaction between microstructure, damage and strength are extremely demanding in terms of computational cost, which limits their use. Our aim is to develop engineering models that have the necessary resolution to reproduce accurately the effects of microstructural damage and yet have sufficient computational efficiency to simulate the differences in the behaviour of engineering components that are caused by variations and changes in the finer microstructure.

Our approach to computationally efficient multiscale modelling is to locally insert the microstructure into a coarser model, but only where such refinement is needed. This is done in the FEMME model for quasi-brittle materials, which has been applied to simulate damage development in a range of materials including SiC-SiC composites and thermal barrier coatings.

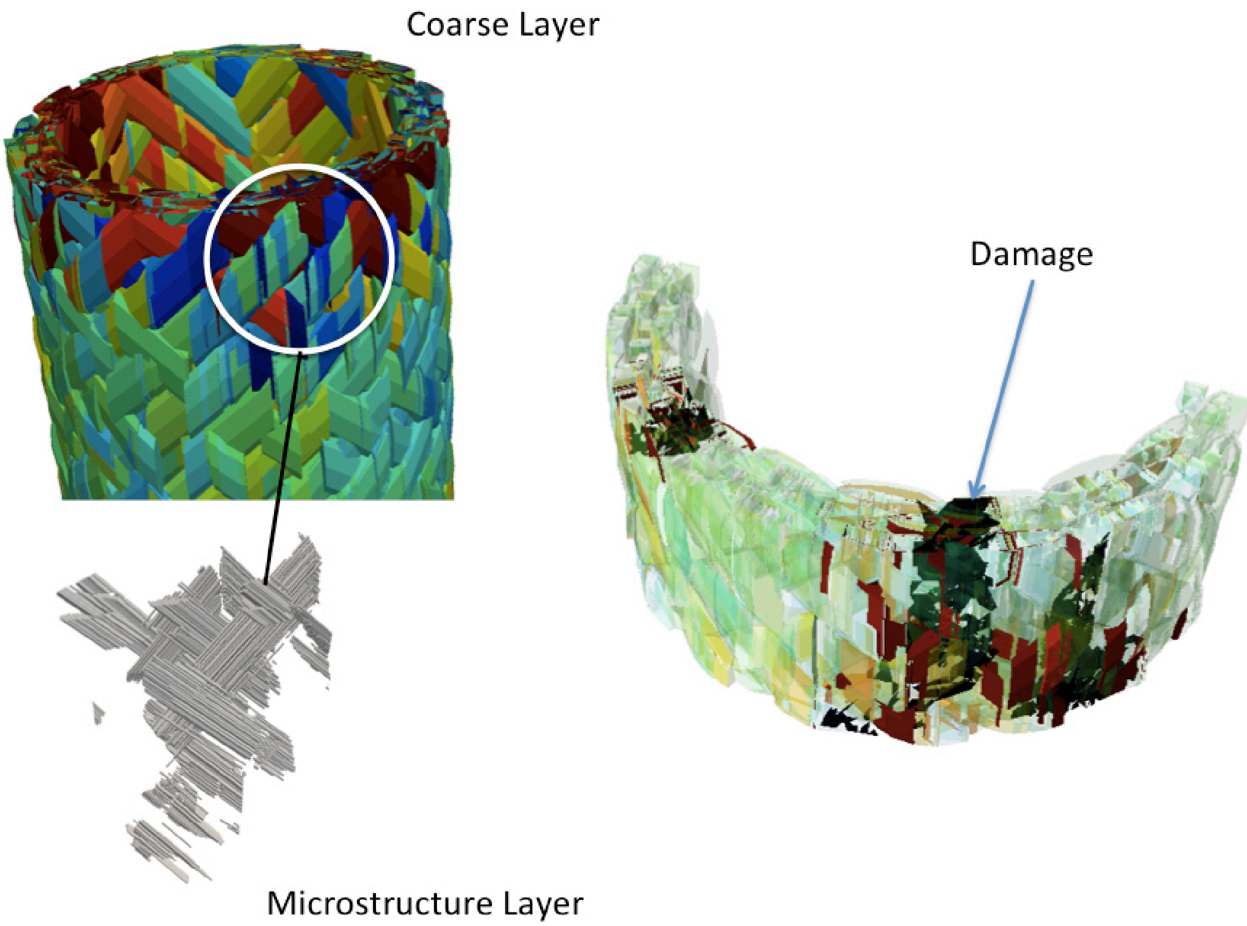

Fig. 2. Visualisation of the coarse and fine microstructure layers of the FEMME multi-scale model of a woven ceramic composite tube (left). The results of a computer simulation of damage development are shown on the left - the pattern of damage is affected by the microstructure. This damage affects the mechanical performance of the composite.

In this paper, the FEMME model is applied to the problem of damage development in a silicon carbide ceramic fibre reinforced silicon carbide ceramic matrix composite tube, which is a cladding for high temperature nuclear fuel. We demonstrate its ability to introduce high fidelity to important aspects of the microstructure into a larger scale model of the component. The numerical simulations describe damage development at a length scale that can be studied experimentally, and can describe the failure of the component under different states of stress, and also examine the sensitivity of the components performance to degradation of material properties.

The model simulations are compared with experimental data that describe the bulk properties of the composite and the development of damage within its structure. These experiments use high resolution X—ray computed tomography and digital volume correlation to observe and measure damage development inside the material. The predicted damage is consistent with experimental observations, although the model requires further development to achieve high fidelity to some microstructural processes such as matrix cracking and fibre pull-out.

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Publication

Multi-scale damage modelling in a ceramic matrix composite using a finite-element microstructure meshfree methodology.
Saucedo-Mora L, Marrow TJ
Philos Trans A Math Phys Eng Sci. 2016 Jul 13