Behavior and damage study of Oxide/Oxide CMCs using in-situ Micro-CT test and Digital Volume Correlation

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Abstract

Ceramic Matrix Composites (CMCs) are lightweight materials with excellent mechanical properties at elevated temperature, making them promising candidates for various advanced applications. Oxyde/Oxyde (Ox/Ox) laminates are particularly relevant for moderate thermo-mechanical loadings due to their favourable balance between mechanical properties and cost. However, these materials experience damage even at low load levels, resulting in an highly non-linear behaviour (1). The determination of a constitutive law requires a precise understanding of their mechanical behaviour, including at the ply level, as well as rigorous observation and measurement of their damage mechanisms.

X-Ray Computed Tomography (CT) is a widely recognised imaging method allowing access to a material structure in 3D provided local absorption coefficients provide enough contrast in the resulting 3D image. In the same way that the observation of a surface speckle pattern can be used to compute a displacement field during a mechanical test (2), the material structure may provide a natural pattern that can be used to compute a 3D displacement field through Digital Volume Correlation (DVC). In addition to the 3D determination of the displacement field, the advantage of CT is that temperature has no effect whatsoever on X-Ray absorption and material contrast. Thus temperature measurements are no different than room temperature measurements if the X-Ray absorption of the furnace windows is put aside. This allows to overcome experimental issues related to measuring strain fields at elevated temperatures (strain gauges, high-temperature speckles for 2D Digital Image Correaltion (DIC)...) and it is one of the most important industrial advantage of this application.

Our study aims to elucidate the damage scenario in Ox/Ox through in-situ micro-computed tomography (μCT) tests. To achieve this, tensile/compression and bending using compression with pivot device are conducted on a 2D woven Ox/Ox with different lay-ups (0/90, 45/-45 and a quasi-isotropic) both at room temperature and up to 700$\circ$C. To address issues

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arising from too small sample sizes, as highlighted by (3),the samples used in this study will present a minimum size larger than 1.5 times the Representative Elementary Volume of the ply (REV). The maximum volume obtained by backprojection of is 4000x4000x4000 pixels, which, at a maximum resolution of 15μm/voxel, allows us to study approximately a 50x50x50 mm area if the Region Of Interest (ROI) at the centre of the sample.

There are two possible approaches to conduct digital images correlation : global or local, which mainly differ in how the displacement field is computed. In the local approach, the studied zone Ω is subdivided into small zones of interest Ω i . For each of these small zones, the average mechanical transformation is estimated between the reference state and the deformed state. This approach has the advantage of being easier to implement and can be easily parallelized, and this is the reason why it is currently the most used correlation method, particularly in commercial software. However, although the results can be interpolated over the entire reference zone Ω, the continuity of the displacement field between sub-volumes is not. In contrast to local methods, global methods rely on defining a continuous kinematic field u(x) over the entire region of interest examined.The formalism of this method is thoroughly described in (4). The main advantage of this approach lies in ensuring the continuity and regularity of u(x) on Ω, thanks to local support from finite elements. This aspect is moreover interesting in the determination of constitutive equations, because the same finite elements framework can be used for DVC and numerical computations. In this study, we will consider a global DVC method using and a tetrahedral mesh created with the software "GMSH", which will serve as local support for finite elements. The global DVC software used is "Kintsugi" (5), which is mechanically regularized (6). In a nutshell, a rigid registration of rigid body motions is performed beforehand to estimate rigid translations and compute an initial solution for the DVC algorithm. The DVC is then conducted in a pyramidal manner to help the system to gradually converge from the largest to the smallest regularization length, starting sometines from binned volumes to full volume for example.

Thus, the mechanical and thermo-mechanical tests mentioned previously are analysed using mechanically-regularized global Digital Volume Correlation (DVC) to access global and local displacements and strains, towards a DVC-based identification of constitutive parameters for a damage model at the ply level (7). In order to guarantee the relevance of the displacement field measurements, for a relatively short scan time to be able to conduct mechanical tests with multiples points (34' per scan). A full signal/noise ratio analysis was performed with formulae suggest by (8) and made it possible to optimize and obtain a standard deviation of 0.05 voxel of the displacement field. This also included a reduction in the effects of beam hardening and noise during scanning, while optimizing local contrasts which are very useful for the displacement field calculation by DVC.

Finally, to integrate these tests into a test/calculation dialogue methodology, nonlinear finite-element simulations will be performed. The comparison between these numerical results and the experimental observations will be presented also the identification with FEMU methods of the ODM constitutive law parameters. This case includes the search and integration of the boundary conditions of the mechanical tests, based on the results obtained by DVC. To understand damage scenarios, especially delamination, a study based on DVC calculation residual is in progress, and is focussed for example, on crack apparition and propagation on (+45$\circ$/-45$\circ$)s lay-up , due to mechanical edges effects in laminated composites.

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