IDENTIFYING STRAINS ASSOCIATED WITH CRACK INITIATION IN CARBON FIBRE REINFORCED POLYMERS USING DIGITAL VOLUME CORRELATION

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Summary: Synchrotron radiation computed tomography (SRCT) was used to investigate earliest stage damage initiation in aerospace grade carbon fibre reinforced polymers loaded *in situ* at various load steps. The ability of digital volume correlation (DVC) to identify the strains associated with crack initiation was also interrogated. It was found that DVC is able to identify strains ahead of crack initiation as well as identify the strains associated with the Poisson effect.

1. INTRODUCTION

The high specific modulus, manufacturing flexibility and somewhat customisable properties of fibre-reinforced polymers (CFRP) means that they have evolved to become one of the favoured choices for weight-critical structural applications [1]. Most practical purposes require a laminate stacking sequence with plies in several orientations to reinforce against multi-axial primary loading and incidental transverse loads [2]. However, off-axis plies are susceptible to fibre/matrix debonding, matrix cracking and delamination, which contribute to failure of the lamina [3-6]. Due to the intrinsic difficulties in experimentally identifying and statistically quantifying initiation, such as scale, number and location of debonds and micro-cracks, widely accepted models for damage initiation, are yet to be established [6], and understanding of controlling factors remains uncertain [7]. Innovative work completed by Borstnar et al [8] illustrates that strains within the constraints of a sub-ply laminate at sub-ply length scales can be captured using digital volume correlation (DVC). In this work, the use of computed tomography and DVC were investigated for their potential as a novel method to aid in the identification of early stage damage initiation in carbon reinforced polymers (CFRP). The findings of the study will be used to inform modelling techniques such as Onset theory, which identifies the first and second strain invariants, dilatational and distortional, as the critical precursors to damage initiation [9].

2. EXPERIMENTAL METHOD

An interlayer toughened epoxy carbon fibre composite material was chosen for the investigation. Three layups, $[0,90]_{2s}$, $[\pm10]_{2s}$, and $[90]_8$, cut into coupons were tested at incrementally applied uniaxial tensile loads to determine where and at what load damage initiated. Computed tomography scans were captured using Synchrotron Radiation Computed Tomography (SRCT) at the Swiss Light Source and European Synchrotron Research Facility (ESRF). Beam energy of 19keV and voxel resolution of 320nm were selected as appropriate parameters to capture early stage damage initiation of the material. Having identified a blurring effect in fibres parallel to the path of the beam, in the $[0,90]_{2s}$ and the $[90]_8$ coupons, scans conducted at the ESRF were done so that these fibres were offset, relative to the path of the beam, at an angle of 15°.The coupons were tested in situ using a custom-loading rig. To ensure that DVC displacement measurements are as accurate as possible, inherent system noise must be determined to distinguish between real and possibly erroneous displacement measurements. This threshold is determined by conducting a noise study. Two volumes of an unloaded, static $[\pm10]_{2s}$ coupon were captured. A comparison of the two static scans, by DVC, should reveal zero displacement. A rigid body motion study was also conducted. The coupon was displaced 5µm in the x direction and the coupon rescanned. This was repeated in the y direction. A comparison of these scans, by DVC, should record this displacement. The results of this noise study were used to determine threshold for measurable strains in the system. Void growth and damage initiation was segmented and quantified using ImageJ™. DVC displacement measurements of the reconstructed volumes were conducted using DaVis 8.1.3 software. Volumes of the loaded coupon were compared against the unloaded coupon and displacements between load steps were mapped and compared.

Image segmentation of this layup showed that damage initiates at the free edge of the coupon, and propagated towards the centre as load is increased. Existing defects are seen to grow and new debonds/cracks form as load is applied. This sub-volume size provided a spatial resolution of 28 μm and a strain resolution between 500 and 1200 με. Results of the rigid body motion study show that in this case DVC is able to track displacement with an error percentage of 4.8%, The coupon was displaced by 5 μm and the DVC software recorded a displacement of 4.9 μm. Displacement in the z direction, along the fibre in a $[\pm10]_{2s}$ layup, proved more difficult to track. DVC relies, like DIC, on a random pattern for the algorithm to be able to calculate displacement of the deformed material. The nature of the fibres in this material means that a stochastic pattern cannot be identified in the fibre direction. As a result the software returned a displacement of zero in the y direction. The inability to track displacements along the fibre has been previously reported in [8]. DVC analysis was conducted on volumes of the loaded $[\pm10]_{2s}$ coupon, and was able to identify dilatational strains. This can be attributed to the Poisson effect. The noise in the system makes it difficult to identify strains at a fibre matrix interface scale; work on noise reduction is on going. As no cracks were identified in this layup, it was not possible to gather information on strain ahead of crack initiation. A visual inspection conducted on volumes obtained from a scan of the $[0,90]_{2s}$ coupons, loaded to 240 MPa, identified a crack in the transverse ply, Fig.1. The region of interest was carefully identified in the scans captured at the lower load steps. A DVC analysis was carried out between load steps to determine whether the strains associated with crack initiation would be identifiable using this method. It was found that DVC was able to identify the strains thus giving us the ability to detect where crack initiation is likely to occur prior to formation.

CONCLUSION

The results of the volumetric post processing have shown that it is possible to identify early stage damage initiation in CFRP under a tensile load using computer tomography. Damage is seen to initiate at the free edge and propagate towards the centre. The results of the DVC rigid body motion study show that detecting displacements along the fibre length is difficult due to the non-stochastic nature of the material. Displacements in the x direction were calculated with a good degree of accuracy. The DVC strain analysis has successfully identified the strains around crack formation and this has encouraging implications for the advancement in the understanding of the physical damage initiation micro-mechanisms in CFRP. Scheduled future studies will further develop the technique, including minimising inherent noise in the system, and lead to the informing and development of an improved modelling capability.

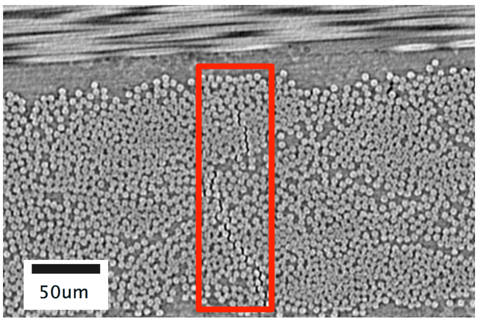

Fig1: Crack identified in the transverse ply of a $[0,90]_{2s}$ coupon. Scan was captured at the ESRF.

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