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Quantifying fibre reorientation during axial compression of a composite through time-lapse X-ray imaging and individual fibre tracking

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ABSTRACT

The sudden compressive failure of unidirectional (UD) fibre reinforced composites at loads well below their tensile strengths is a cause of practical concern. In this respect and more generally, analytical and numerical models that describe composite behaviour have been hard to verify due to a lack of experimental observation, particularly in 3D. The aim of this paper is to combine fast in-situ X-ray computed tomography (CT) with advanced image analysis to capture the changes in fibre orientation in 3D during uninterrupted progressive loading in compression of a UD glass fibre reinforced polymer (GFRP). By analysing and establishing correspondence between a sequence of time-lapse X-ray CT images of the composite, we are able for the first time to follow each fibre and quantify the progressive deflection that takes place during axial compression in the steps leading up to fibre micro-buckling and kinking. Even at just 25% of the failure load, fibres have started to tilt in approximately the direction of the ultimate kink band. The rate of tilting increases as the composite approaches the collapse load. More generally, our approach can be applied to investigate the behaviour of a wide range of fibrous materials under changing loading conditions.

1. Introduction

Composite materials are used extensively in advanced structures where properties such as high stiffness and low weight are required. In particular, carbon and glass fibre reinforced polymers (CFRP and GFRP) are being employed increasingly in aero [1] and ground transportation, as well as in environmentally sustainable energy production systems, such as wind turbines [2]. Therefore, it is crucial to understand their performance under realistic loading conditions with the ultimate goal of optimising performance through the use of analytical or numerical models [3]. Currently, the lack of confidence in these models means that expensive experimental mechanical testing is relied upon in the development of new composite structures, and is still the gold standard for quality control in industry [4]. What is more, this lack of confidence in the prediction of composite behaviour, together with high safety requirements, leads to an unnecessary over-engineering of the components.

The compressive strengths of unidirectional (UD) composites are typically significantly below their tensile strengths [5]. This is because many of the mechanisms of compressive failure are dictated largely by the matrix properties, in contrast to the tensile properties which are dictated by the fibres. A number of failure mechanisms under compression have been described in Refs. [6–8], the most important of which for the current study is fibre micro-buckling (see Fig. 1(b–c)). Longitudinal splitting along the fibre direction is also a potential damage mode (see Fig. 1(d)). Fibre micro-buckling is highly sensitive to the initial fibre misalignment [6,9]. As a result of the composite manufacturing process, the fibres are, in general, not perfectly aligned with the axial direction. This means that when compression is applied, some level of shear is induced in the region of the misaligned fibres. When the local shear stress exceeds the matrix shear yield strength, the matrix yields and fibres buckle. In other words, the compression strength of a UD composite relies on the ability of the matrix material to keep the fibres straight [5]. Fibres finally fracture when the strain on the compressive/tensile side of the fibre exceeds the fibre's compressive/tensile failure strain, and a kink band is formed [10]. Although for the reasons discussed above many researchers believe that fibre misalignment plays a big role [11,12], and the degree of lateral constraint on the fibres from the matrix is important [13], the initiation mechanism for fibre micro-buckling is still a subject of debate. This is largely because of the

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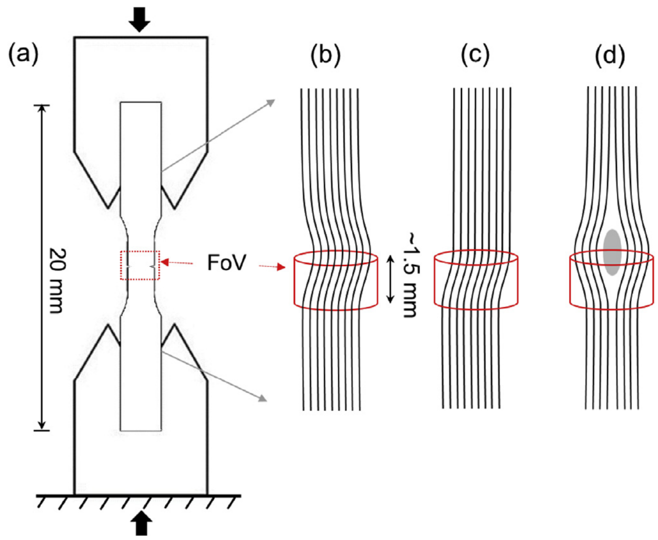

Fig. 1. Schematic illustration of a loaded specimen and damage modes associated with axial compression. (a) Composite specimen geometry and loading condition, and potential damage modes associated with axial compression failure of unidirectional fibre composite, namely (b–c) fibre micro-buckling and (d) longitudinal splitting.

lack of direct evidence of the fibre movements in the moments leading up to micro-buckling and the point at which this becomes a kink band. The difficulty in capturing experimentally the precursors to failure is partly due to the small levels of misalignment required to trigger instability, and partly because of the sudden and catastrophic nature of the instability when the kink bands form.

In recent years, optical and scanning electron microscopy have increased in image acquisition speeds. This has been exploited to study the development of kink bands in composites loaded in-situ [14] by observing the surface of the composites. Guynn et al. [14] and more recently Moran et al. [15] have observed experimentally in 2D that fibres buckle before a kink band is formed. However, the stage of fibre deflection prior to the onset of kink-band formation, which is expected to influence the kink-band geometry, has not yet been captured experimentally. This is partly because 2D characterisation techniques cannot capture information out of the observed plane. X-ray computed tomography (CT) enables 3D imaging of FRP specimens containing many fibres at a resolution where individual fibres can be resolved [16]. Wang et al. [17] employed post-mortem X-ray CT to study kink-band formation and reported the 3D morphology of kink bands for the first time, where deformation out of the kinking plane was also observed within the damage zone. Moreover, it is possible to scan a sample while it is loaded in-situ in compression so that the evolution in fibre orientation under load can be observed in 3D from no load towards failure. Conventional tomography, even at synchrotron sources, is too slow to capture the onset of micro-buckling [18,19]. However, ultra-fast imaging (~ 500 – 10,000 2D images per second) is now possible on some beamlines, which enables the events leading up to failure to be captured by X-ray CT [20]. Using ultra-fast in-situ imaging, Wang [21] obtained a time-series of 3D X-ray CT images leading up to kink bands, extending the work in Ref. [17]. The quantification of the small fibre reorientation preceding the kink-band formation requires advanced image analysis.

The focus of this paper is on combining in-situ X-ray CT with advanced image analysis with the purpose of providing an experimental description of the changes in fibre orientation during progressive loading in compression. Fibre orientations have been estimated from tomograms [22–24] without previously segmenting individual fibres, but the accuracy of these estimates is highly dependent on the quality of the tomograms. However, if individual fibres can be segmented beforehand, the accuracy of the individual fibre trajectories can be ascertained prior to computing fibre orientations. Additionally, segmentation of individual fibres opens up the possibility of following the changes in trajectory for each individual fibre across successive loading steps. Methods that can segment individual fibres from tomograms of UD FRPs, where fibres are closely packed, have been applied to measure fibre geometry from high-quality data [25] and also from lower quality scans [26–28]. The method by Czabaj et al. [26] involves a time-consuming validation of the determined fibre trajectories and is therefore applicable to small volumes containing a limited amount of fibres. Sencu et al. [27] built a micro-mechanical model with a few fibres that had been segmented from bundles orientated in different directions. The focus of Emerson et al. [28] was on determining individual fibre orientations. The method by Emerson et al. ensures a representative characterisation of the composite's microstructure due to its ability to find a large amount of fibres and delineate their centre line with high precision, even at resolutions where a fibre diameter is covered by just 4 pixels [29].

Our proposed methodology is to characterise the trajectory of individual fibres in the as-manufactured condition in 3D from X-ray CT images and then to quantify, as compressive loading progresses, the deflections by the analysis of a time-lapse CT image sequence. The aim is to capture precursors to fibre micro-buckling and kinking in 3D for the first time, in the moments leading up to kink-band formation. The material system employed in the experiment was an end-tabbed UD GFRP rod specimen (see Fig. 1(a)).

2. Materials and experimental procedures

2.1. Manufacturing and preparation of composite sample

A modified resin infusion technique referred to as small-scale resin infusion, as reported by Wang et al. [17], was used to fabricate the 2 mm diameter UD E-glass fibre (12 μm in diameter)/epoxy (Huntsman Araldite LY564/XB3486) composite rods. Specimens with a reduced gauge section of around 1.5 mm in diameter over 3 mm in length were prepared from the manufactured composite rods. Fig. 1(a) shows the specimen geometry for in-situ testing. So as to localise the damage site, a groove around the circumference was made using a razor blade giving a notch depth between 100 μm and 200 μm. The two ends of the specimen were then glued with an epoxy adhesive into chamfered steel end caps so that end-splitting damage could be avoided. This resulted in a length of the composite rod equal to 20 mm and an overall length of the specimen of ~28 mm.

2.2. Ultra-fast synchrotron X-ray computed tomography (CT) imaging under in-situ compression

Ultra-fast imaging was performed at the TOMCAT beamline from the Swiss Light Source (SLS). A monochromatic beam with a mean energy of 20 keV was used, and the specimen-detector distance was set so as to aid micro-crack detection with a level of phase contrast. 500 projections were acquired over 180° rotation and the exposure time for each projection was 2 ms. These settings equate to a fast acquisition at 1 scan per second. The data-sets were reconstructed at TOMCAT using the Paganin algorithm [30]. The pixel size of the reconstructed CT data-sets is 1. 1 μm.

Specimens were end-loaded in a tension-compression in-situ loading rig developed at INSA-Lyon [31], which could be accommodated for dynamic imaging. The compression tests were conducted under displacement control at the rate of 1 μm^{-1}. For the sample presented in this paper, an initial static scan was performed at 0 N, followed by interrupted scans at intermediate loads (200 N and 600 N), and then by continuous dynamic scans as the expected failure load was approached. Each interrupted CT scan started at an arbitrary angle, so there is an angular difference between each data-set in the *xy* plane.