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A numerical study on the influence of composite wrinkle defect geometry on compressive strength

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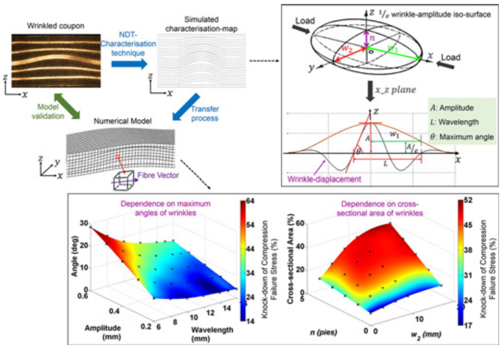
HIGHLIGHTS

- A new methodology is presented to rapidly create finite element models of wrinkled composites based on NDT information.
- The suggested approach allowed a rigorous study to rank wrinkle-parameter importance using a simulator of NDT information.
- Maximum angle in load direction was the key parameter affecting compressive strength, with wavelength being of secondary.
- Increasing wrinkled region extent perpendicular to load direction also correlated with decreasing compressive strength.

GRAPHICAL ABSTRACT



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ABSTRACT

Out-of-plane winkling in continuous-fibre reinforced composites has a significant influence on compressive failure stress, which needs to be considered and evaluated during the design, manufacture and inspection stages, to achieve high-performance composite components. With the development of a three-dimensional characterisation based on non-destructive testing methods and finite-element modelling, it is possible to combine the two techniques to give a prediction of mechanical performance using directly measured geometry. This paper uses a new methodology developed for combining non-destructive characterisation and numerical analysis techniques to automatically create a series of models with controlled wrinkle geometry. It has been possible to determine the dependence of compressive strength on various wrinkle-severity and wrinkle-extent parameters. The outcome shows a dominant dependence on the maximum wrinkle angle in the load direction, with an additional dependence on the wrinkle wavelength for larger wrinkle angles. In terms of the extent of the wrinkled region, the strength reduces as the wrinkle extent in the load direction becomes concentrated locally or the wrinkled proportion of the cross-sectional area (perpendicular to the load) increases.

1. Introduction

Although composites materials are widely used, from sport components to aircraft structures, the prediction of their failure processes and experimental characterisation of their performance remains a challenge, as demonstrated by the World-Wide Failure Exercises (WWFE)

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[1,2]. To add further complexity to the prediction of failure, variations can occur in the material internal *meso*-structure as a result of manufacturing processes. Out-of-plane misalignment of the fibre paths, generally known as 'wrinkling', is a relatively common phenomenon in thick components or curved sections [3] and is known to have a significant influence on mechanical performance. Wang et al. [4] manufactured out-of-plane fibre waviness in AS4/8552 (resin/fibre) composites by three methods and, based on their experimental work, Lemanski et al. [5] developed FE models to simulate the compressive failure process. Both experimental results and modelled predictions indicated a reduction in compressive strength of about 54% when peak misalignment angle increased to about 22°. Mukhopadhyay et al. [6] also showed the significance of wrinkles on compressive strength. They introduced wrinkles by selectively inserting or removing prepreg strips in the 90° plies of quasi-isotropic laminates. Both experimental results and numerical predictions showed that a maximum misalignment angle of 12° resulted in a 30% knock-down of compressive strength. This reduction of compressive performance related to wrinkle angles has also been investigated experimentally and numerically by Ferreira et al. [7]. Other research has identified this negative influence and summarised the dependence of the compressive-strength knock-down on amplitude [8], or the ratio of amplitude-to-wavelength [9,10]. Therefore, during the design, test, simulation and performance-assessment stages for a composite component, the potential negative influence of any wrinkles needs to be carefully considered. It is important to have a full understanding of how wrinkles influence the compressive failure of laminates, in order to understand which wrinkle parameters (severity, shape or extent) play a more important role. This information can then be used to determine the metrics that should be measured non-destructively when wrinkles occur during manufacture.

A number of authors have attempted to characterise the fibre paths and variations from ideal trajectories in composite materials using non-destructive testing (NDT) methods [11–18], covering the eddy current [11,13], X-ray computed tomography (CT) [12] and ultrasonic techniques [14–18]. The development of this field using eddy currents is currently limited to the two dimensional (2D) response at the surface, so it is not currently capable of full 3D characterisation. Hence the latter two methods are more likely to be used in the industry. For the X-ray CT technique, its 3D data has been used to assist the creation of numerical models for estimating the influence of detected defects on structural integrity. Alghamdi et al. [19] successfully created FE models based on X-ray CT data, but their models did not include any failure mechanisms. The group of Makeev et al. has made a significant contribution to this field [20–22]. In their most recent research [22], the in-plane and out-of-plane fibre waviness was characterised based on the X-ray CT technique and was transferred into FE models with modified LaRC04 [23] failure criteria included, the predicted results showed good agreement with the experimental results. Ultrasonic characterisation has been more widely used in the component-quality evaluation stage as it has greater capacity for large-size components than X-ray CT. Freemantle et al. [24] developed FE models from ultrasonic NDT data for composites containing delaminations after suffering an impact load. Their model predictions showed good agreement with the test results for flat panels but their method did not include wrinkle characterisation or modelling of any fibre or matrix damage mechanisms. Sandhu et al. [25] characterised the fibre path for wrinkles, using 'multiple field image analysis' on ultrasonic B-scan data to determine wrinkle amplitude, wavelength and location. They proposed that this 2D information could be used with a prismatic assumption to create a 3D FE mesh through the extrusion of the 2D geometries but no results from this method were reported. Smith et al. [14–17] demonstrated inversion of ultrasonic full-waveform scans to obtain three-dimensional (3D) maps for both out-of-plane ply wrinkling and in-plane fibre waviness. Their method is the basis on which numerical models are created in this paper. In their research [26], they pointed out the measurement capability for wrinkle angle at every location could be possible up to a wrinkle angle of 15°, and the resolution for a complete map of fibre angles is dependent on scan pitch, with a minimum of around 0.2 mm. This state-of-the-art capability has not been available in industry, but is being transferred into commercial software applications. The development of such non-destructive methods raises the necessity for measurement guidance for manufacturing imperfections.

Composite components with out-of-plane wrinkles under compressive loading have been shown by the authors to fail due to a combination of delamination, matrix cracking and fibre failure [6]. There have been many theories proposed for the prediction of onset and propagation of each mode of failure for embedding in numerical models. The following failure-mode theories, validated by the authors [6], are those used in the present work reported in this paper. For the initiation of delamination, a quadratic damage-initiation criterion [27] was applied and then a Power-Law [28] criterion was used to govern the mixed-mode interface failure. Matrix cracking is controlled by the criterion suggested by Puck et al. [29,30], with the assumption that a crack happens on a plane inclined at a specific angle. Finally for the fibre damage, the kinking model is based on Pinho's work [31,32], which suggests that the fibre failure occurs on a rotated plane, triggered by shear stress due to the initial fibre misalignment and the final region of fibre failure forms a kink band. The authors [6] combined the failure mechanisms stated above in finite-element models for wrinkled composite laminates and demonstrated that the resulting models possessed the capability to predict the whole failure process in detail.

Even though the effect of wrinkling on composite strength has been shown to be significant, there is still no consensus on which parameters, or combinations thereof, have the most significant influence on failure stress. Amplitude (A), wrinkle wavelength (L) and maximum angle (θ), defined in Fig. 1(a), have each been proposed by different authors to describe a wrinkle. Lemanski et al. [5], Mukhopadhyay et al. [6] and Sutcliffe et al. [12] chose maximum angle to define wrinkle severity, while Fedulov et al. [33] used wrinkle height as a fraction of laminate thickness. Hsiao and Daniel [10] used amplitude and wavelength to characterise wrinkles, assuming a sinusoidal wrinkle shape, and proposed a representative volume truncated at a single period of the wrinkle, with amplitude reducing linearly from the mid-plane to the sample surfaces. Later Caiazzo et al. [34] used a polynomial to describe the wrinkle shape, with amplitude reducing linearly to the sample surfaces, and used the peak height and the wrinkle extent in the load direction as the 'gross' measures of the defect size. More recently, El-Hajjar and Petersen [35] proposed a Gaussian function to characterise 'bell-curve' wrinkles, the maximum amplitude (waviness height) at one surface was designed to be diminished at the opposite one, thus forming samples with one flat surface and one concave 'bell' surface, and the wrinkle-amptitude reduction through the thickness related to the distance from the maximum-amplitude surface. In the results, they chose 'waviness height' to describe the wrinkle severity or extent. The application of Gaussian functions to describe the wrinkle distribution was adopted in this paper, but the range of wrinkle metrics investigated is significantly greater.

This review of the literature shows a lack of consensus over the key wrinkle metrics for non-destructive measurement. It illustrates the need for a rigorous and controlled multi-dimensional parametric study to identify and understand the interdependencies of parameters and determine a hierarchy of wrinkle-parameter importance, which could provide guidance for the industrial quality-assurance process for components with manufacturing induced wrinkles. The objective of this paper is to use a validated modelling approach to explore the parameter space in terms of a wrinkled component's compressive strength. This could not be achieved experimentally in a systematic and rigorous way due to the very large number of highly controlled specimens that would be required and the difficulty of precisely controlling specific parameters of wrinkles during the manufacturing process; nor has it been possible in the past using numerical models because of the time and manual effort required to create each different model.