Validating Finite Element Models of Composite Structures Containing Fibre-Waviness Defects

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Abstract

A technique is demonstrated for creating finite element models of complex manufacturing defects found in composite structures. Specimens containing defects in the form of fibre-waviness have been produced and the orientation of fibres in the affected area measured non-destructively using ultrasound. Ultrasonic measurements of waviness were then used to create a finite element model of the defect. The strain field at the defect location was measured using digital image correlation and used to validate the finite element model. The model was shown to accurately describe the influence of the defects and thus the technique could be extended to predicting the residual life of a composite component.

Introduction

Carbon fibre composite components are already utilised across many industries but further adoption of this material is limited by the costs associated with its manufacture and its potential sensitivity to defects. These defects can take many forms such as local porosity or misalignment of fibres in the laminate, which is referred to as fibre-waviness. When a defect is located in a composite component it is often difficult to assess its severity and thus it is common for defective composites to be replaced, often unnecessarily [1]. With increases in the automation of non-destructive evaluation (NDE) techniques and the computing power used to analyse the resulting data it is now possible for the spatial distribution of a defect to be measured and used to form a finite element model of the component with the defect incorporated into the model [2]. Such models could then be used to predict the behaviour of the component in service or even under extreme loads. By making these predictions, defects that may once have been considered too severe to be present in a component may become allowable.

In order for computer simulations of components to be used in decision-making, it is necessary to quantify how well the model represents the real world conditions. There are many potential issues that could cause a model to be unacceptable: the NDE technique may have poor resolution when assessing the component, the algorithms used to infer local material properties from NDE measurements could be flawed or the method of incorporating the local properties into the model may be inadequate. One method of assessing if the model is a correct representation of the component is to quantitatively compare predictions of strain on the surface of the component with strain fields that have been experimentally measured using techniques such as digital image correlation (DIC). If the model accurately simulates the strain field then greater confidence can be held in residual life predictions. In this paper quasi-isotropic coupons have been produced with fibre-waviness defects. Ultrasonic NDE was used to quantify the fibre-orientation in the coupons and the maps of fibre-orientation used to modify the material properties in a finite element model. Both the physical coupons and their associated models were then loaded in four-point bending and the model validated using full-field strain data measured with DIC.

Experimental Method

Thirty-six quasi-isotropic laminates with a $[0/90/45/-45]_s$ layup were produced using unidirectional carbon-fibre prepreg (RP507, PRF Ltd., UK). The prepreg was laid-up over a former that had a short arc at the centre of its profile with flat surfaces extending from the ends of the arc, resulting in a shape similar to a gable roof. As the prepreg layers were laid over the former, the outer layers were longer at the arc section than the layers closest to the former. When the uncured laminate was removed from the former and flattened the fibres on the top of the prepreg buckled forming local waves that resulted in the fibre-waviness defect. The laminates were then cured in a hot press according to the manufacturer's instructions and cut down to 40 by 220 mm coupons using a wet-diamond saw.

Each coupon was then assessed using pulse-echo C-scan ultrasound. The amplitude of echoes reflected from the ply containing fibre-waviness were recorded resulting in greyscale images, shown in the bottom-left of Fig 1. The local fibre-orientation is visible in the intensity or 'texture' of the amplitude C-scan data and thus is measurable. The discrete 2D Fourier transform was applied to small subsets of the C-scan data and the local orientation of the fibres in the subset determined by analysing the spectral image. The measured fibre-orientation field was then used to define the material orientation for individual elements in an Abaqus model corresponding to the same location as in the physical specimen. The strain field on the surface of the simulated specimen was then predicted for a bending moment of 18 Nm applied using four-point loading. The physical specimens were similarly loaded to 18 Nm and DIC was used to measure the strain field on the top surface of the specimen at the region of fibre waviness.

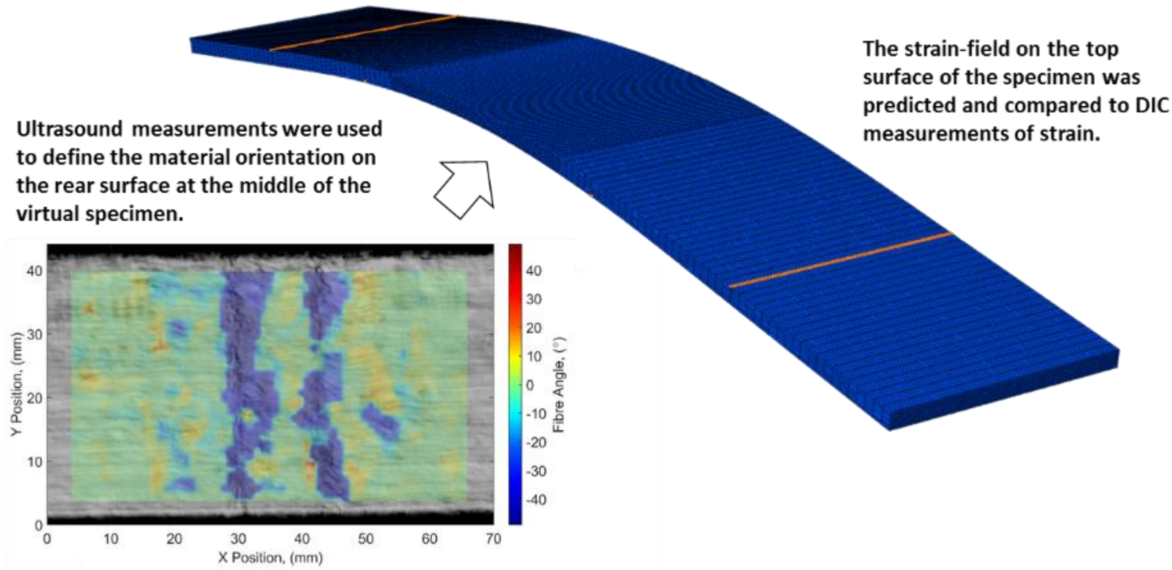

Fig 1: Illustration of how fibre orientation measured using ultrasound (bottom left) was incorporated into the model (top right).

Discussion

Comparisons between the experimental and simulated strain fields, left and centre of Fig. 2, were made using image decomposition [3]. Image decomposition is the process by which the dimensionality of the strain field is reduced such that the strain data can be represented by a small number of shape descriptors. Comparisons of strain data from the experiment and the simulation can then be made using only the shape descriptors for each data set. If the model is valid then when the shape descriptors for the model and experimental data are plotted against each other they should be contained within a narrow region defined by the measurement uncertainty of the DIC system, right of Fig 2. When this validation process was repeated for each of the 36 specimens the associated model was found to be valid in every case except for one. By quantitatively comparing the experimental and model strain fields it is also possible to determine how well the defect characterisation code is performing and thus make comparisons between different algorithms without subjective decisions.

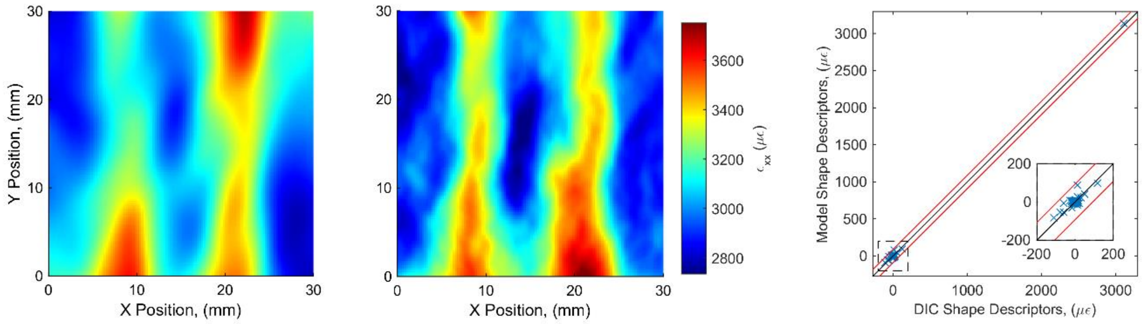

Fig 2: Predictions of surface strain (left) and DIC measurements (centre). The validation diagram (right) shows that the model is valid given the uncertainty of the measurement system, the inset shows an enlarged version of the boxed region on the main graph.

Conclusion

This work demonstrates a technique for creating finite element models using ultrasound measurements of manufacturing defects in carbon fibre laminates. Quantitative comparisons between experimental and model strain fields have demonstrated that the technique is capable of assessing the influence of the defects on the structural performance of the laminate.

Acknowledgements

WJRC is studying on an EPSRC CASE Award PhD sponsored by Airbus.

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