CREATING FIBRE-WAVINESS DEFECTS IN LAMINATES AND PREDICTING THEIR REMNANT STRENGTH USING A STRAIN-BASED NON-DESTRUCTIVE EVALUATION TECHNIQUE

W. J. R. Christian[1], F. A. DiazDelaO[2], K. Atherton[3] and E. A. Patterson[4]

[1]School of Engineering, University of Liverpool, L69 3GH, UK
Email: w.j.r.christian@liverpool.ac.uk, Website:
https://www.liverpool.ac.uk/engineering/staff/william-christian/
[2]Institute for Risk and Uncertainty, University of Liverpool, UK
Email: f.a.diazdelao@liverpool.ac.uk, Webpage:
https://www.liverpool.ac.uk/engineering/staff/francisco-alejandro/
[3]Airbus UK, Filton, UK
Email: kathryn.atherton@airbus.com, Webpage: http://www.airbus.com/
[4]School of Engineering, University of Liverpool, L69 3GH, UK.
Email: eann.patterson@liverpool.ac.uk, Webpage: https://realizeengineering.blog/

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Abstract
A technique is demonstrated for creating controlled levels of in-plane fibre waviness. Using this technique, a large batch of specimens were created and then characterised by ultrasonic non-destructive evaluation and a novel strain-based evaluation technique. Predictive empirical models of remnant strength were fitted to the measurements and the strain-based predictions were found to have significantly lower levels of uncertainty relative to ultrasound based predictions.

1. Introduction

Fibre reinforced polymers allow engineers to tailor the strength of a structure to the loads expected during service, this is achieved by exploiting the anisotropic properties of the fibres. However, when the fibres are misaligned, the structure can be substantially weaker than its intended ultimate load. One cause of misalignment is fibre-waviness, where the fibre path is buckled into the shape of a transverse wave. This defect is categorised into two types, in-plane waviness and out-of-plane waviness. Ultrasonic non-destructive evaluation (NDE) is often used to locate and characterise these defects but it performs poorly when assessing remnant strength. Recently strain-based NDE has been found to be more effective than ultrasound for predicting remnant strength after impact damage [1], this study explores whether similar improvements can be achieved for waviness defects.

Whilst several studies have explored the effects of out-of-plane waviness on remnant strength [2, 3] there has been less research on in-plane waviness. One cause of this is the difficulty of creating in-plane waviness representative of that encountered in industry. One method is to lay prepreg plies over a curved aluminium plate. Once layup has been completed the plate is flattened causing the fibres in the prepreg laminate to buckle [4]. However, this results in in-plane waviness that is uniformly distributed across the laminate instead of a localized defect. In this study, a novel technique based on machined aluminium formers is introduced that can be used to create controlled levels of localised in-plane waviness in laminates. A large batch of quasi-isotropic laminates were created, that contained waviness at six different levels of severity. The waviness within the specimens was then characterized and its effect on remnant strength determined.

2. Experimental Method

The specimens were manufactured using unidirectional prepreg plies (RP507UT210, PRF, UK) with a $[0_2/90_2/45_2/\text{-}45_2/\text{-}45_2/45_2/90_2/0_2]$ layup. The nominal waviness was varied using a set of formers, shown in (Fig. 1), which consisted of two angled surfaces connected by an arc section. The severity of the waviness was changed by varying the radius of the arc section and quantified as nominal waviness as [5]:

$$Nominal\ Waviness = \frac{t_u}{r + t_u} \tag{1}$$

where r is the radius and t_u is the thickness of the uncured prepreg. Six specimens were manufactured at nominal waviness levels of 0%, 10%, 15%, 17.5%, 20% and 25%, resulting in a total of 36 specimens. After layup the specimens were removed for the formers and flattened between two plates causing the fibres on the top of the laminate to buckle at the arc section due to the change in shape. The laminates were then cured in a hot press at 130°C for 45 minutes under 2.5bar of pressure.

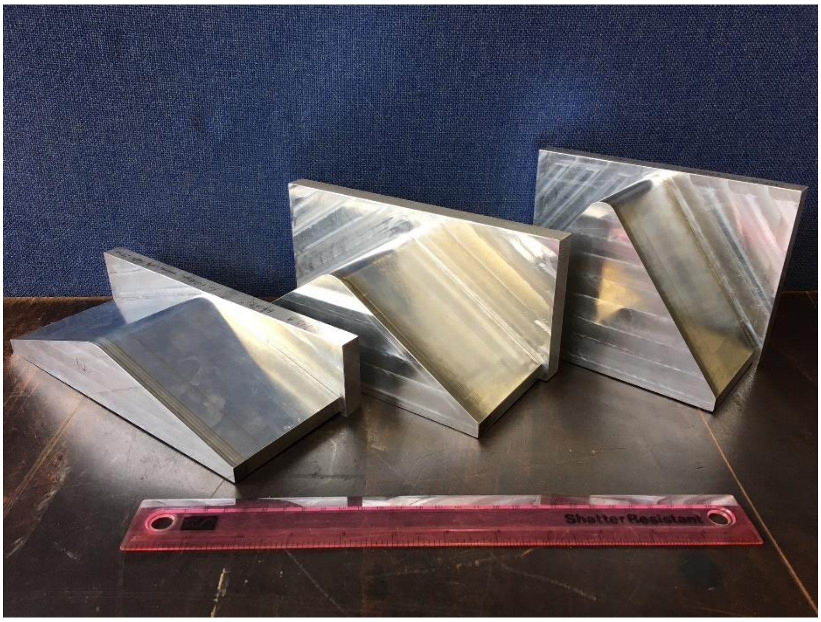

Figure 1. Three of the formers for creating defects with nominal waviness of 10%, 17.5% and 25% (left to right).

Two techniques were chosen to quantify the waviness in each specimen. The first technique was ultrasonic characterization, where an ultrasonic amplitude C-scan was performed on the defective ply. A texture caused by the fibre tows was visible in the resulting C-scan image. The image was then processed using a Fourier transform based algorithm to determine the fibre-orientation field for the defective plies across the scanned area, described in [6]. The second technique was based on residual strain measurements. As the specimens were cured between flat plates, the cured coupon would also be expected to be flat. However, the specimens that contained defects were found to have a slight curvature. This curvature was due to the fibre-misalignment at the defect location causing thermal stresses during curing. Digital image correlation (DIC) was used to measure the deflection of the laminates from a flat plane, w. From this deflection the residual strain field was then calculated as [7]:

$$\epsilon_{x,res} = -\frac{t_c}{2}\frac{\partial^2 w}{\partial x^2} \tag{2}$$

where, t_c is the thickness of the cured laminate.

After characterization the laminates were loaded to failure in four-point bending. The ultimate bending moment was recorded as the remnant strength of the defective laminates. The laminates were loaded with the defective ply placed in compression.

3. Results and Discussion

The waviness defects were detectable in both the ultrasound data and the residual strain fields, an example of both these data-fields are shown in (Fig. 2). Both measurement techniques were found to be capable of locating defects and similar features can be identified in both data-fields. For example in (Fig. 2), a band of highly misaligned fibres are visible in the fibre-orientation field at x=0mm whilst a corresponding band of high residual strains was visible at the same location in the residual strain field.

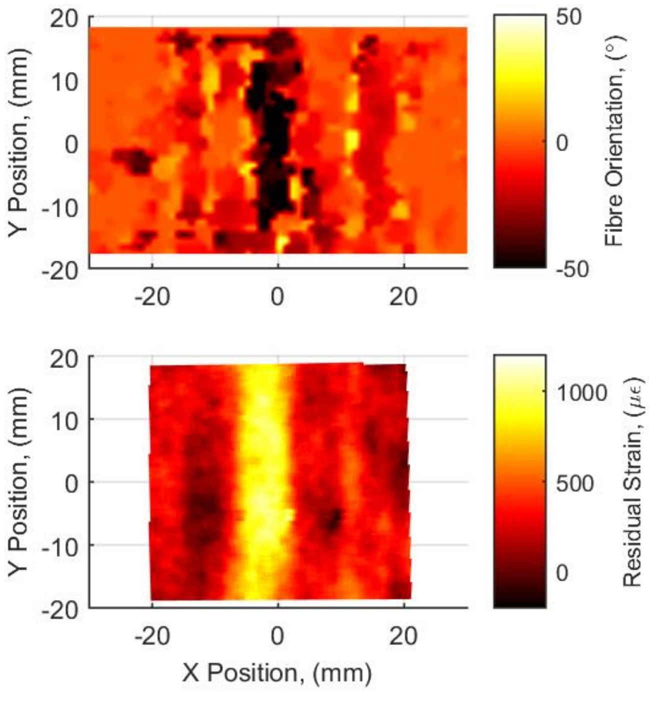

Figure 2. A waviness defect characterised using ultrasound (top) and residual strain measurements (bottom).

The severity of the defects measured using ultrasound were quantified by calculating the root mean square (RMS) of the fibre-orientation field. The severity based on residual strain measurements was quantified by calculating the mean value of the residual strain field. The remnant strength was found to linearly decrease as the mean residual strain increased until a threshold for residual strain was reached. Above this threshold the remnant strength did not decrease. A similar relationship was observed for the ultrasound based measurements. Two empirical models were fitted to the data using piecewise robust Bayesian regression [5]. These models were capable of predicting remnant strength based on either the RMS of the fibre-orientation or the mean residual strain. The empirical model fitted to the mean residual strain data is shown in (Fig. 3). The uncertainty on the predictions generated by these models was quantified using leave-one-out-cross-validation (LOOCV) as 3.10Nm and 1.87Nm for the ultrasound and strain-based predictions respectively. Improving the accuracy of remnant strength predictions could reduce the number of unnecessary repairs, and thus decrease the operating costs of composite structures.

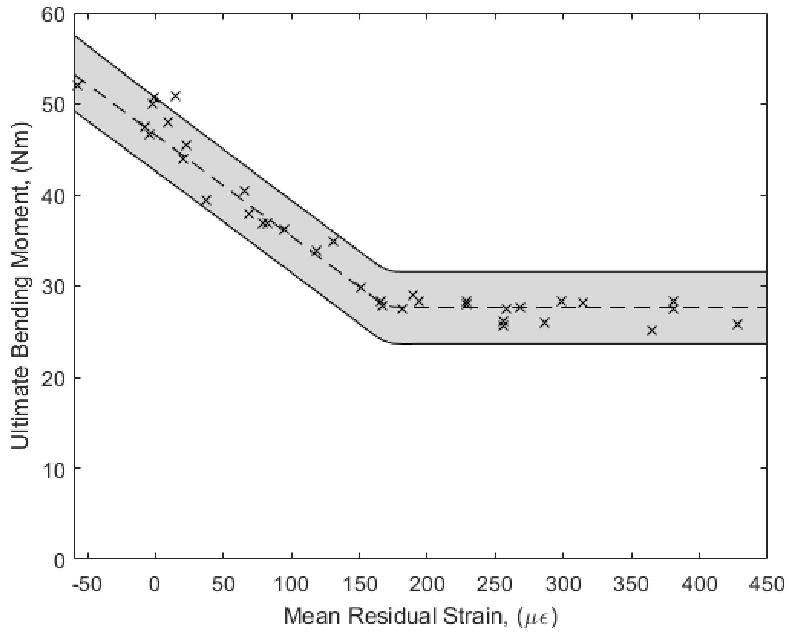

Figure 3: A predictive empirical model of remnant strength based on residual strain. The dark grey region indicates the 95% credible interval for predictions.

4. Conclusions

A new method of creating fibre-waviness defects in laminates has been used to create a large batch of specimens. These specimens have been characterised with an ultrasonic non-destructive evaluation technique as well as a novel technique based on the measurement of residual strains. When predicting the remnant strength of the defective laminates the strain-based predictions were found to have an uncertainty that was 60% of that for ultrasound based-predictions.

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