An optimisation-based technique for predicting strains in defective composite laminates

X.N. Li[1,2a], E.A. Patterson[1], W.J.R. Christian[1] and W.C. Wang[2]

[1] School of Engineering, University of Liverpool, Liverpool, UK

[2] Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu, Taiwan

[a]Xiaonan.Li@liverpool.ac.uk

Abstract. A new technique was developed to investigate the mechanical behaviour of carbon fibre reinforced polymer (CFRP) laminates containing in-plane fibre waviness. Experimental and numerical analysis of strains developed during four-point bending tests were performed on the defective specimens. Digital image correlation (DIC) was used to measure the full-field strains in the specimens when they were loaded to failure. The severity of the waviness defects in the specimens was characterised by ultrasound C-scans, yielding fibre orientation data for use in finite element (FE) models. The loading process was simulated using ABAQUS and the generated FE models to compute strains. The measured and predicted strain fields were decomposed into feature vectors using orthogonal polynomials to reduce the data dimensionality and make comparisons, where the similarity was represented by calculating the Euclidean distance between the two sets of vectors. The FE models were updated using the particle swarm optimisation (PSO) algorithm to calibrate the mechanical properties. The updated FE model was shown to be a good tool for predicting the magnitude and shape of strain around the defects.

Introduction

CFRP materials have been used in aerospace industry for many years due to their relatively high specific stiffness compared with traditional materials. However, the performance of CFRP components is affected by various defects, such as voids, debonds, in-plane and out-of-plane fibre waviness. Few studies have been conducted on in-plane fibre waviness defects, as they are not easy to characterise and even more difficult to induce in laboratories. In-plane fibre waviness is the deviation of fibres from the designed direction within a ply, and it is known that these defects are where localised stress concentrates, which leads to the final failure of a defective component. Fibre waviness occurs during the manufacturing process and due to four reasons. The first one is the different thermal expansion coefficient of the fibres and matrix, which results in distortions during curing. The second reason is because of the friction through the thickness and sliding of fibres caused by external compression during the consolidation stage. The third reason is warping effects, which result from the interaction between a component and tool. The fourth one is when continuous fibres are laid on a curved part causing them to buckle [1].

Characterisation of fibre waviness is difficult, as the fibre diameters are small and there are uncertainties and measurement errors that cannot be overlooked, especially for a low degree of fibre waviness. Currently the most common method for characterising fibre waviness in industry is non-destructive testing using ultrasound C-scan, which can be used to scan a region of interest and provide the surface morphology of the region. The surface morphology is presented as a 2D grayscale image, which can be processed to provide fibre orientation data for generating FE models. There is always a difference between the measured data and the FE model predictions of strain fields, which arises mainly because of the difficulty in identifying the correct material properties [2].

FE model updating is a process to tune a model to better represent reality. Fundamentally, this process is an optimisation problem of minimising the distance between measured data and predicted data by identifying the appropriate input parameters of the FE model. PSO is an evolutionary algorithm that can be applied to solve optimisation problems, and thus it can be used for FE model updating purposes. PSO is applied by randomly generating a number of particles in a multi-dimensional solution space. Each particle represents one possible solution to the objective function, which in this study, is the Euclidean distance between the two sets of feature vectors decomposed from the measured and predicted strain fields. Each particle can adjust its position in the solution space by learning from the other particles and its own best solution at each iteration, and convergence can be achieved when all the particles are close enough to the global best solution within a specified tolerance range [2].

To better understand the effect of fibre waviness on the mechanical performance of the defective components, in this study, a novel approach was developed for the prediction of bending strains. The approach involves fibre waviness characterisation using ultrasound C-scans, image processing using Fast Fourier transformation, image decomposition using Chebyshev polynomials, and FE model updating using PSO.

Experimental method

Six different severities of in-plane fibre waviness were induced into CFRP specimens using the techniques described in [3], with 6 specimens having each level of severity giving 36 specimens in total. These specimens were characterised using ultrasound C-scans to capture images of the defective area. These images were then processed using an algorithm based on the 2D Fourier transformation to quantitatively characterise the fibre orientations in the region of specimens where waviness was expected. The fibre orientation data were used to create FE models in Abaqus, to simulate a four-point bending test. DIC was used to measure the full field strains when the specimens were loaded to failure by a four-point bending rig. Strain fields from the FE predictions and the DIC measurements were then decomposed using Chebyshev polynomials to yield feature vectors [4]. PSO was used to search for the best set of material properties by minimising the Euclidean distance between the two sets of feature vectors.

Results and Discussion

The convergence history of the PSO is shown in Fig. 1, which demonstrates that with increasing iterations, the Euclidean distance firstly decreased dramatically, then gradually converged. The reduction in the Euclidean distance explains that by updating the FE models, the discrepancy between measured data and predicted data has been lowered to a reasonable level, which can be confirmed in Fig. 2. The measured strain field (left) was compared with the predicted strain fields (middle and right) in Fig. 2. The middle strain field in Fig. 2 shows that strains were underestimated when using material properties from literature, while the updated FE model using calibrated properties can predict both the high strain locations and magnitude more accurately. Image decomposition was used to reduce data dimensionality, simplifying the comparisons between the two strain fields without losing important features. PSO was efficient at calibrating the mechanical properties for updating the FE models to give better predictions of strains during quasi-static bending. It should be noted that during the loading process, high strains were more likely to appear at the regions where the fibre waviness was the most severe, and this was observed in both the observations and predictions.

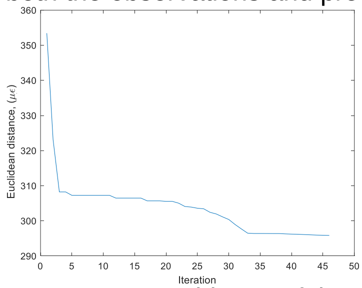

Fig. 1 Convergence history of the PSO.

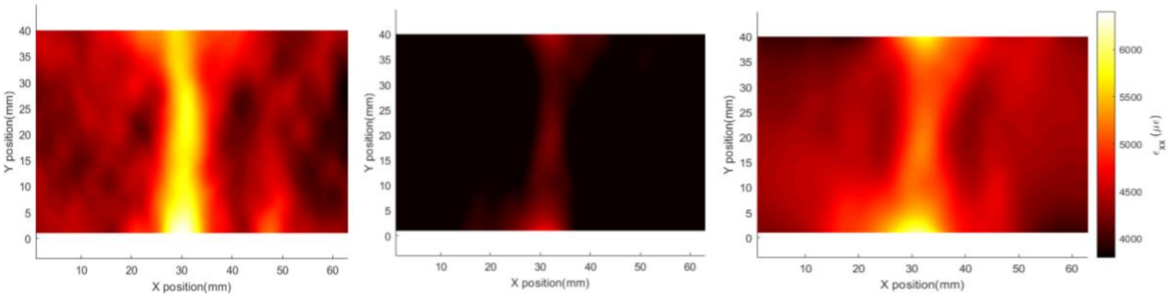

Fig. 2 Bending strains measured by DIC (left), predicted by a FE model using literature data (middle) and by an updated FE model (right).

Conclusion

A novel technique for identifying high strain locations and predicting strain fields has been developed. This method can be used for evaluating specimens with in-plane fibre waviness under loading. With further development of the FE models, the progressive failure behaviour of a defective specimen could be simulated, and the ultimate strength predicted. The technique has the potential for automating the process of estimating the failure load of a defective CFRP component based on non-destructive test data.

References

[1] P. Kulkarni, K.D. Mali, and S. Singh: *Composite Part A*. Vol. 137 (2020).
[2] J. E. Mottershead, M. I. Friswell: *Journal of Sound and Vibration*, Vol. 167 (1993), p. 347-375.
[3] W. J. R. Christian, F. A. DiazDelao, K. Atherton, E. A. Patterson: *Royal Society Open Science*, Vol. 5 (2018).
[4] CEN Workshop Agreement 16799:2014, 'Validation of computational solid mechanics models', (2014).