Compression Fatigue Characterisation of Fibre-Reinforced Polymer Composites

M.A. Battley[1,3a], N. Shepherd[1,3], J. Rout[2,3] and T.D. Allen[2,3]

[1]Department of Engineering Science, University of Auckland, New Zealand,

[2]Department of Mechanical and Mechatronics Engineering, University of Auckland, New Zealand

[3]Centre for Advanced Materials Manufacturing and Design, University of Auckland, New Zealand

[a]m.battley@auckland.ac.nz

Abstract
This paper discusses compression fatigue characterisation methods that have been developed and applied to two different types of materials and laminates. The first of these investigated the effect that different stitch patterns have on fibre alignment, damage initiation and compression fatigue failure for glass-fibre Non-Crimp Fabric (NCF) reinforced laminates, and the second developed a new specimen design for characterisation of compressive fatigue failure characterisation of thick, highly directional carbon-fibre prepreg laminates.

Possible Sessions

Fatigue & Fracture, Testing of Composite Materials

Introduction

Significant amounts of research have been undertaken to better understand the failure mechanics of fibre-reinforced polymer composites in compression. However, the primary focus of much of this has been on monotonic loading rather than fatigue. Challenges of characterising compression fatigue behaviour include applying load to specimens during fatigue without causing premature failures, avoiding buckling failures and difficulties that standardised loading methods and test fixtures cause for diagnostic methods such as full-field strain measurement and Acoustic Emission monitoring.

Non-Crimp Fabrics (NCF) are a class of dry textile comprised of layers of aligned fibre tows held in place by thin stitching yarns. The stitched architecture of the dry fabric allows for good handling and drapability, while aiming to minimise the fibre crimp or waviness compared to a two-dimensional woven fabrics [1]. Despite this, the degree of misalignment present in NCF composites is still generally greater than would be expected from a unidirectional preimpregnated material [1–3]. Fibre misalignment is a key parameter for predictions of composite compression strength [4], so characterisation of the degree of waviness is important, as is its effect on damage initiation and evolution during compression loading. Capturing this behaviour for NCF laminates requires a larger gauge area than is typically used in standardised compression test methods such as ASTM D6641, and also the use of diagnostic methods.

As industries move towards replacing major structural components with composite materials - such as wing spars, turbine roots, and hydrofoils - there is a need to develop testing capabilities for laminates with thicknesses of tens of mm. Prior research to enhance compressive measurements' accuracy, precision and reliability has addressed three main sources of variability: stress concentrations, prevention of column buckling and achieving a uniform strain gradient through the gauge thickness. These challenges are greater for thick laminates. The use of shear load transfer is not well suited to fatigue tests to variations in load transfer, slippage of grips and undue shear stress development in the specimen.

Methodology and Results

Fibre Misalignment. Measurements of fibre misalignment in NCF composites are key to enabling predictions of compression failure by fibre kinking. The in-plane waviness may be influenced by the wide range of stitching parameters, such as stitch spacing, thread tension, thread linear density, thread material, or stitching pattern. An FTMA-MultiRotate algorithm was applied to measure in-plane fibre alignment from back-lit low-resolution and low-magnification photographs of stitched glass fabrics. From these measurements, statistical analysis was conducted to quantify the difference in severity and distribution of fibre misalignment across stitched fabrics constructed using different stitching patterns. Three different stitched fabrics were considered (chain, tricot, and mixed), each consisting of two fabric sides (front and rear), for a total of six different fabric faces. 120 back-lit photographs were taken from each fabric face, and from each photograph 9126 measurements of fibre alignment were extracted, each measurement representing the area-averaged value within a 315μm square cell. A threshold was applied to these measured values to segment measurements of the stitching from measurements of fibre tows, followed by a morphological cleaning process to further isolate the values of interest. The remaining valid measurements of fibre alignment were then collated into datasets for each face, fabric, and side for further statistical analysis.

Fig. 1 shows a heat map of typical alignment variability from this analysis. Fig. 2 shows the 99th percentile misalignment values for all six fabric faces with error bars to plus or minus three standard deviations. Here, the combined effects from the scale and shape parameters can be more clearly seen. Fabric faces with a higher 99th-percentile misalignment exhibit a distribution that contains more extreme (higher) fibre misalignments, and therefore can be considered to be more severely misaligned overall. From Fig. 2 it can be seen that the front faces across all three fabrics exhibit more severe mis-alignment than their corresponding rear faces. The difference between front and rear faces is greatest for the mixed fabric, which contains both the most highly misaligned face overall (front), and the least highly misaligned face overall (rear). The rear face of the mixed fabric shows a 99th-percentile misalignment of 5.64°, while the front face of the same fabric shows a much larger 99th-percentile mis- alignment of 9.42°, an increase of more than 67%. Foam core sandwich beams were manufactured and tested in a servo-hydraulic testing machine to characterize the fatigue behaviour of the different NCF laminates, providing large enough gauge regions to include multiple stitch units and enable the use of Acoustic Emission monitoring to characterise damage initiation and evolution.

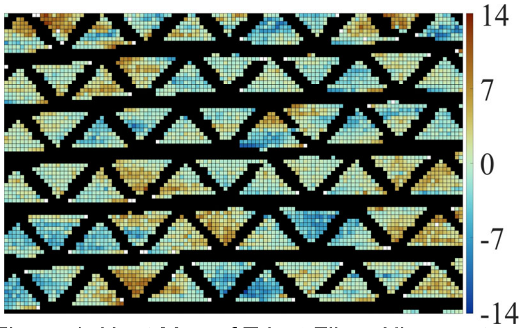

Figure 1. Heat Map of Tricot Fibre Alignment

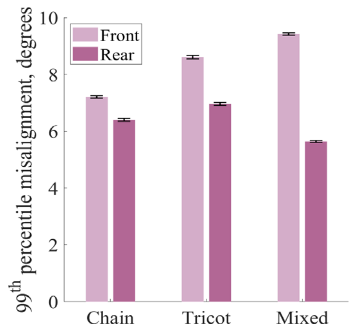

Figure 2. Percentile misalignment values

Fatigue Testing of Thick Laminates. Development of a new test specimen and loading approach for thick composites was based on an end-loaded specimen with external tabs to increase the area available for end loading, tailor shear transfer into the specimen gauge region and stabilize the specimen against buckling. A detailed finite element numerical model was developed and experimentally validated to enable optimisation of the specimens' tab parameters and to investigate the potential of laminate tailoring near to its outside faces to minimize stress concentrations. Fig. 3 shows an example result of the normalised compressive strain plotted against the axial position for 15-degree (Left) vs 90-degree (Right) tapered tabs, Each line represents a ply within the laminate, with the results demonstrating that tabs need to have a very small angle to minimize stress concentration at its end. The strains at 50mm show the gradient through the laminate thickness at the centre of the gauge length. Results also show that the stress concentrations at the ends of the tabs can be minimised though addition of off-axis plies on the outside of the main unidirectional laminate.

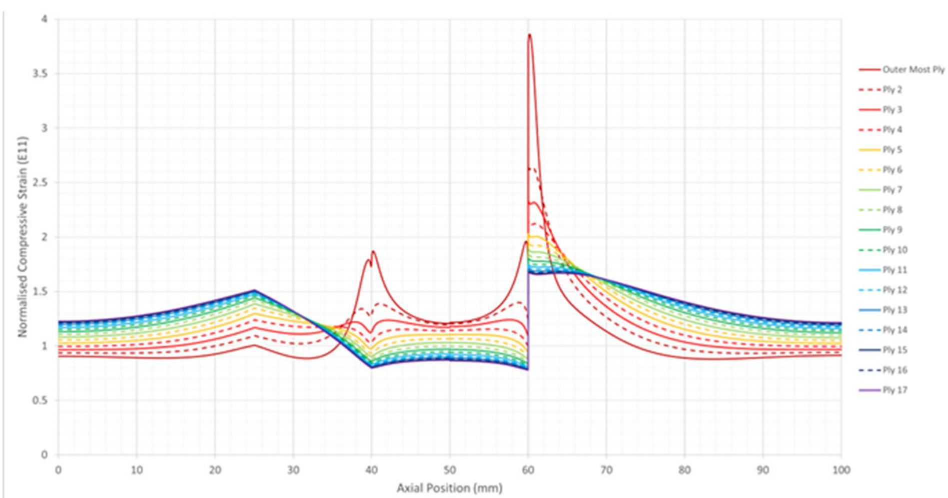

Figure 3. Normalised compressive strain plotted against the axial position for 15-degree (Left) vs 90-degree (Right) tapered tabs. Each line represents a ply within the laminate, from the outside to centre.

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