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Automated counting of off-axis tunnelling cracks using digital image processing

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A B S T R A C T

An automated method for counting propagating matrix tunnelling cracks for use in mechanical testing of Glass Fibre Reinforced Plastic (GFRP) laminates under quasi-static and fatigue loading is presented. White light images are captured from specimens during the loading. The transmitted light is used to detect the cracks in the images, which are then processed to count the cracks as they develop and grow through the duration of the test. The reproducibility and accuracy of the image processing is demonstrated using simulated transverse crack densities and patterns. The methodology is demonstrated and validated experimentally using two different laminate stacking sequences of the type $[0/-\theta/0/\ \theta]_s$. The results related to the crack density evolution are shown to be consistent with results from the literature.

1. Introduction

For more than four decades, fatigue life prediction for composite laminates subjected to multiaxial loading has been a subject of significant interest due to the increasing use of composite materials in many industrial applications. The nature of fatigue damage in composite laminates is complicated, as many cracks initiate, propagate and coalesce, making mechanistic modelling challenging. Therefore the vast majority of fatigue life prediction models are phenomenological, e.g. Refs. [1] [2], [3], [4]. These models are based on the assumptions adopted in Refs. [5], where failure of laminated composites can only occur in the fibres and matrix. The models attempt to predict when the failure modes occur and how they influence structural behaviour, thereby taking into account the physical damage mechanisms in a simplistic way. A recent extensive review of phenomenological multiaxial fatigue criteria [6] has shown that for some multiaxial load cases the models gave non-conservative predictions. Due to the phenomenological nature of the models, no apparent reason for the large discrepancies between model predictions and experimental observations can readily be obtained, which further questions their general validity. Therefore, in Ref. [6] it is emphasised that there is an urgent need for developing an improved understanding of the underlying damage mechanisms, alongside the inclusion of physical damage mechanisms in predictive multiaxial fatigue models.

Many kinds of micro damage may evolve during the fatigue life of laminated composites. One of the most common damage modes is intralaminar cracks in the laminate layers, which are through-the-thickness (tunnelling) cracks in the matrix and fibre debonds propagating along the fibres. These cracks are commonly called transverse and off-axis matrix cracks. Defining the material damage state in terms of off-axis cracks provides an important parameter, which is a true physical internal state variable that can be treated using the well-developed framework of fracture mechanics. Several analytical models for predicting the stiffness degradation as function of the off-axis crack state in each laminate layer have been proposed, see e.g. Refs. [7–9], but widely accepted models describing the initiation and evolution of off-axis cracks during fatigue loading of multidirectional laminates are yet to be proposed. This may be attributed to the tedious and labour intensive work required to define the damage state, which predominantly up until now has been accomplished by manually counting the propagating cracks. The mainly manual and very labour intensive

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damage characterisation process has so far limited the scope and size of experimental campaigns, and/or significant data parameterisation, which makes it difficult to draw firm conclusions and to derive statistically representative material parameters. The overarching aim of the present research is therefore the development of a robust and accurate method for automatic quantification of the damage in GFRP laminates in terms of off-axis cracks. The development of such a methodology will enable the efficient and accurate determination of physical damage state parameters, and this is a prerequisite for the development and validation of more reliable off-axis crack evolution models.

1.1. Off-axis crack state detection

Several experimental measurement methods have been used to successfully detect off-axis cracks in GFRP laminates. The diverse selection of techniques include thermoelastic stress analysis (TSA) [10], digital image correlation (DIC) [11], acoustic emission [12], X-ray [13], X-ray Computed Tomography (CT) [14], Ultrasonic C-scan [13] and transilluminated white light imaging (TWLI) [15–19]. X-ray, X-ray CT and Ultrasonic C-scan require the fatigue test to be interrupted to conduct measurements and are not relevant in the context of the present research. TSA and DIC can be used to obtain in-situ surface measurements of the sum of maximum principal stresses and the component strain fields respectively. However, depending on the laminate layup the stress/strain redistribution on the surface caused by the presence of a crack may be below the strain resolution of the methods. Furthermore, the number of independent measurement points is very limited compared to TWLI. Acoustic emission is an in-situ and automated measurement method [12], but the damage mode connected with acoustic events has to be hypothesised or calibrated with other techniques.

TWLI as used in Refs. [15–19] represents a cheap, fast and data-rich in-situ detection method for GFRP laminates because of their transparent nature, which permits transmitted white light to be used as a means of detecting cracks. Based upon the above reasoning TWLI was found to be the most favourable method for crack detection, and accordingly was chosen as the basis for this research.

1.2. Off-axis crack state quantification

TWLI works by illuminating the material from one side and then acquiring images of the light transmitted through the material from the other side. The transmission of light is disrupted by the presence of off-axis cracks making them visible in the acquired images. A significant limitation of TWLI is that it is restricted to transparent materials (like GFRP). Previous research that has utilised TWLI for counting off-axis cracks includes little or no automation of the procedure. In Ref. [19] an automatic acquisition and crack counting system for in-situ transverse crack counting was developed. However, spatial information on the crack pattern perpendicular to the loading direction was neglected, which means that the method is limited to counting the number of transverse cracks, and not the length and location of each individual crack. In Ref. [15] the automatic crack counting system was used to count transverse cracks in two different laminates. The same authors [16] studied off-axis cracks, but due to the limitations of their method they had to resort to manual quantification of the damage state in terms of crack initiation and crack saturation from images acquired using a video camera and in-situ microscopic edge examination. Off-axis cracks in multiaxially loaded tubes made from non-crimp GFRP fabrics were studied [17] and the damage state quantified in terms of crack densities at different lifetimes. Crack density measurements were conducted by interrupting the fatigue tests and then acquiring images of the cracks using a light microscope upon several areas of interest and the off-axis cracks were counted by visual inspection of the images. Off-axis cracks in flat coupon test specimens made from GFRP prepreg were studied in Ref. [18] using backlight illumination and a standard SLR camera to automatically acquire images of the off-axis cracks throughout the fatigue life of the specimens.[3] The damage state and evolution were quantified in terms of crack density and crack growth rate (CGR) of isolated cracks. The crack density was counted manually by dividing cracks into eight separate bins. The reason for this was to ease the manual counting process. The CGR measurements were obtained by manually measuring the length of isolated cracks at different numbers of cycles. From the above literature review, it is clear that a means of automatically counting both transverse and off-axis cracks is essential to avoid tedious manual work and avoid human errors in the counting process, enabling reproducible results that are obtained in a fast and reliable manner.

1.3. Translaminar crack state qualification

A novel algorithm for qualification of translaminar crack state called Automated Crack Counting (ACC) to automatically detect, monitor and measure the length and position of each observable crack layerwise in GFRP laminates with arbitrary layup is presented. ACC uses TWLI to detect and track cracks and digital image processing to filter images. The image filtering serves two purposes; 1) produce a clear image of the cracks, and 2) to filter out cracks from other layers to define the crack state layerwise instead of laminate-wise. The length and location of each individual crack is measured from the filtered images using a simple heuristic procedure. The new ACC procedure is validated based on simulated crack densities which are used to benchmark ACC against a known input, and to provide guidelines for the choice of measuring volume versus expected crack density. Furthermore, the ability of the ACC to detect and measure cracks in their full length is validated against microscopic examination. Results from fatigue tests of two different GFRP laminates are presented, which represent challenging test cases, because they are made from stitched fibre mats and vacuum assisted resin transfer moulding used for e.g. wind turbine blade laminates. The stitching thread has a different refractive index than the glass fibres and matrix material, so the stitching thread appears as a texture in the material, which exacerbates crack counting. It is shown that ACC allows for fast, accurate and reproducible detection as well as unprecedented quantification of the translaminar crack state.

2. Automated crack counting methodology

An image and a sketch of the experimental setup used for fatigue testing of GFRP laminates and acquiring in-situ images of off-axis cracks using TWLI are shown in Fig. 1a. A digital camera is placed on one side of the specimen and the backlight illumination on the other side. The specimen is also illuminated on the front side for the purposes of image compensation. Fig. 1b illustrates the specimen geometry along with important features on the specimen and Table 1 summarises the properties of the optical system.

The RMS noise used for computing the signal-to-noise ratio (SNR) was determined by subtracting two reference images and

[3] In Ref. [18] it is not stated when the images were acquired during the fatigue tests. At Comptest2015, 8-10th of April 2015, Madrid, M. Quaresimin (corresponding author of [18]) elaborated on the experimental procedure in a private discussion, and informed that the test specimens were unloaded each time an image was acquired. Hereafter the test was recommenced.