Composite Structures 106 (2013) 882–889

Contents lists available at SciVerse ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Damage development in open-hole composite specimens in fatigue. Part 1: Experimental investigation

O.J. Nixon-Pearson [a,*], S.R. Hallett [a], P.J. Withers [b], J. Rouse [b]

[a] Advanced Composites Centre for Innovation and Science, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK
[b] Henry Moseley X-ray Imaging Facility, School of Materials, Grosvenor St., University of Manchester, Manchester M1 7HS, UK

ARTICLE INFO

Article history:
Available online 15 June 2013

Keywords:
Carbon fibre/epoxy
Damage
Fatigue
Open hole

ABSTRACT

An extensive experimental program has been carried out to investigate and understand the sequence of damage development throughout the life of open-hole quasi-isotropic IM7/8552 carbon-fibre/epoxy laminates loaded in tension–tension fatigue.

Samples were initially quasi-statically loaded to failure to determine an average strength, σ_{UTS}. Specimens were then cyclically loaded at 5 Hz at various amplitudes to $1 \times 10^{+6}$ cycles or to failure (15% loss of stiffness), which ever occurred first.

Interrupted fatigue tests were carried out with peak amplitude at 60% of the ultimate static load (60% severity) in order to determine the 3D sequence of damage events using X-ray Computed Tomography (CT). Matrix cracking at the surface ply and initiation of matrix cracks in the subsequent plies lead to delaminations that progress through the thickness, and ultimately to the propagation of delamination at the −45/0 interface all the way back towards the end tabs. The log (number of cycles to failure) decreased linearly as the maximum fatigue stress level increased.

1. Introduction

In many applications fibre reinforced composite materials are replacing metals due to their excellent corrosion and fatigue properties as well as offering weight saving advantages. Although composites are perceived to have a greater fatigue life than comparable metallic components, there is still only a limited amount of research available in the open literature characterising the development of fatigue damage. This can be a critical shortcoming, in terms of long-term service lifetime assessment as failure by fatigue represents the most uncertainty.

Furthermore, many applications, particularly rotating components, involve repeated loading cycles, heightening the need for a better understanding.

The behaviour of composite materials containing notches has been the subject of considerable research during the last three decades [1] since quasi-static notched strength is an important design driver. Along with the growth in composites usage the understanding of size effects and the mechanisms of notched failure are becoming increasingly important areas of research [2]. The complex failure and damage mechanisms which occur during loading of a composite laminate are enhanced in notch failures due to the presence of stress concentrations. This causes a range of effects that are not observed in unnotched composites. The notch sensitivity of a laminate is dependent on the size of laminate, hole/notch size, quality of machining (drilling of holes and cutting of the samples), ply stacking arrangement, ply and laminate thickness, and lamina constituents. These factors can produce effects which can also interact with one another enhancing the individual effects [3]. Under fatigue loading these interactions are likely to be enhanced since the relative damage growth rates will not be the same and matrix failure modes (e.g. delamination) are likely to become more dominant before fibre failure.

In order to better understand the way in which notched composites fail in fatigue it is first necessary to understand the mechanisms by which sub-critical damage develops at loads below ultimate failure, even in the quasi-static case. One of the early works in this area was that of Kortschot and Beaumont [4]. Sub-critical damage in notched composites takes the form of delamination and axial splitting in the 0° plies, and matrix cracking in the off-axis plies. The stress concentrations are redistributed around the notch and therefore the onset of failure is delayed.

Early fatigue studies of notched composite materials were undertaken by Spearing and Beaumont [5,6] predominantly using cross ply laminates. They developed a new approach to modelling the post fatigue strength and stiffness in notched composites showing how the observation of notch tip damage can be quantified by the extent of individual failure processes. The notch tip

* Corresponding author. Tel.: +44 01173315504.
E-mail addresses: on5405@bristol.ac.uk, on5405@googlemail.com (O.J. Nixon-Pearson).

0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2013.05.033

damage zone grows under tensile cyclic loading in a stable manner, with the shape and size of the damage zone depending on the laminate geometry, fibre, matrix and interfacial properties [5,6].

Spearing and Beaumont concentrated on tension–tension fatigue of notched Carbon/Epoxy (T300/914) and Carbon/Polyetheretherketone (PEEK) laminates using an R ratio of 0.1. NDT techniques included X-radiography to produce images of the damage. It was also shown how prolonged exposure to the zinc iodide dye penetrant can accelerate the growth of damage in the specimens [6].

More recently Broughton et al. [7] have carried out a study on open-hole tension–tension fatigue behaviour of a quasi isotropic glass-fibre reinforced plastic GFRP laminate under constant amplitude and block amplitude loading. They have shown that longitudinal strain, stiffness and surface temperature can be used to assess damage progression, fatigue life, and also for predicting notched fatigue performance. They also showed how the application of various measurement tools such as fibre-Bragg gratings (FBG) and digital image correlation (DIC) can be used to highlight localised sub-critical damage at the hole edge. They did not however conduct a detailed study of the damage mechanisms and sequence of events occurring.

Ambu et al. [8] have investigated the effect of damage on the residual strength of open-hole laminates subjected to fatigue by DIC also finding it a useful tool clarifying the roles played by various failure modes on the residual properties of open-hole laminates.

Others such as Mall and Weidenaar [9] have studied notched fatigue behaviour. Cross ply $[0/90]_{2S}$ and unidirectional $[0]_8$ silicon-carbide fibre reinforced glass ceramic matrix-laminates were tested at room temperature. A fatigue limit of 10^6 cycles was used for the tension–tension condition followed by the fully reversed condition and it was found that the damage in tension–compression far exceeded that under tension–tension conditions with failure occurring well short of 10^6 cycles. The cross ply laminate had shown both longitudinal and transverse cracks in the tension–compression tests, but only transverse cracking for tension–tension tests.

Aymerich and Found [10] compared the open-hole fatigue performance of carbon/PEEK and carbon/epoxy laminates loaded in tension–tension with the following stacking sequences: $[\pm45/0/90]_{2S}$ for carbon/epoxy laminates and $[\pm45/0/90]_{2S}$, $[45/90/-45/0]_{2S}$ and $[0/45/-45/90]_{2S}$ for carbon/PEEK laminates. Their primary objectives were to compare the damage accumulation during static and cyclic loading of the two material systems as representatives of the two classes of tough and brittle matrix composites. They showed that fatigue failure is never reached before 10^6 cycles for the carbon/epoxy laminates even for stress levels very near to the static strength. Whereas the carbon/PEEK laminates had relatively poor long term fatigue performances because the absence of early matrix cracking and delamination favoured fibre fracture.

Recent work [11–13] has demonstrated the power of high resolution X-ray CT for characterising damage progression in notched carbon–epoxy specimens when statically loaded to failure highlighting the accumulation of splits, cracks, delaminations and fibre fracture. This is helping to establish a growing understanding of the processes and consequences of damage development in quasi-statically loaded notched composites. Nevertheless only a limited amount of work has focused on fatigue damage characterisation for notched composites.

In this paper (part I) we examine the role of matrix cracking and its interaction with delamination in determining the mechanism and overall sequence of failure events in fatigue for quasi-isotropic laminates. A layup of $[45_2/90_2/-45_2/0_2]_S$ was chosen as this fails by delamination in the static case [3]. Given the importance of the role of delamination in notched failure [14], it was important to characterise in some detail, a case leading to complete failure by delamination and to compare and contrast static and fatigue failures. X-ray computed tomography has been used to visualise failure events in 3 dimensions, in an unambiguous, and detailed manner for the fatigue of notched quasi-isotropic laminates for the first time. In part II [15], this information will be used to assess the performance of fatigue delamination models [16] to predict failure.

2. Experimental methods

2.1. Mechanical testing

Earlier work on the scaling effect in quasi-static open-hole tension specimens [3] was repeated to ensure consistency of results and to determine the static failure load on which to base the peak fatigue amplitudes.

Quasi-isotropic laminates based on carbon fibre epoxy (IM7/8552) with a $[45_2/90_2/-45_2/0_2]_S$ layup and containing a centrally located hole were tested in quasi-static tension and also in tension–tension fatigue. The hole and specimen size were chosen such that the number of samples could be made from a reasonably sized composite plate. In previous work on static testing of this case, delamination was the dominant cause of failure [14]. This failure mode of greatest interest in fatigue and thus the specimen dimensions chosen are the smallest that fail by delamination [3]. This choice also allowed sufficient spatial resolution for CT imaging.

The UD prepreg system – IM7/8552 from Hexcel has a nominal ply thickness of 0.125 mm. The laminates were cured according the cure cycle recommended by Hexcel [16]. Each specimen had a thickness of 2 mm, width of 16 mm, and gauge length of 64 mm, with a central hole diameter of 3.175 mm (Fig. 1). Glass fibre cross-ply end tab material, with a constant end tab length of 50 mm was used for both static and fatigue tests. The specimens were cut using a water cooled diamond saw and the holes were drilled using lip and spur tungsten carbide drill bits.

For static failure and interrupted tests, the specimens were loaded with a displacement rate of 1 mm/min until failure. As in Ref. [3], a load drop of greater than 5% on the load displacement was taken to represent failure of the specimen.

Both quasi-static and fatigue tests were carried out using an Instron MJ6272 servo-hydraulic test machine with hydraulic grips. A lateral grip pressure of 12.4 MPa was applied to ensure there was no slippage when in contact with the end tab material. The Instron Wavemaker software was used to apply a sine wave loading cycle and to capture the data. All quasi-static and fatigue tests were carried out at standard laboratory conditions (21 ± 3 °C, 50 ± 10% relative humidity).

The fatigue tests were run with peak amplitudes at various percentages of the (average) static failure load, this is what is commonly defined as severity in the literature. Each fatigue test was run in load control using a constant amplitude, with an R ratio of 0.1 and frequency of 5 Hz. Each test was left to run to 10^6 cycles unless failure (defined as a 15% loss of stiffness) occurred prior to reaching this limit. 10^6 cycles is commonly used in the aerospace industry and is appropriate for the number of load cycles experienced during the useful life of an aircraft. Fatigue tests were carried

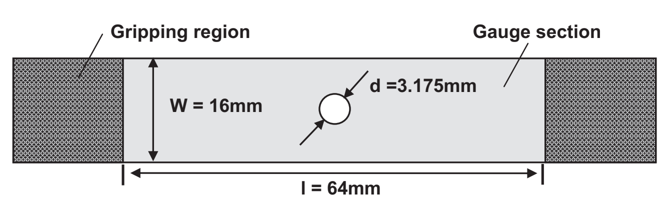

Fig. 1. Specimen geometry.