International Journal of Fatigue 32 (2010) 60–65

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Influence of woven ply degradation on fatigue crack growth in thin notched composites under tensile loading

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ARTICLE INFO

Article history:
Available online 21 January 2009

Keywords:
Woven fabric composite
Fatigue
Crack propagation
Linear elastic fracture mechanics

ABSTRACT

This paper deals with the fatigue of the through-the-thickness crack propagation in thin notched composite laminates made of two glass woven plies. It highlights the different crack growths between warp and weft directions of the woven ply. Experimental results show a decrease of the crack growth rate per cycle with the increase of the crack initiation time. Moreover, it has been shown that it is necessary to take into account the fatigue damage of the woven plies in term of loss of rigidity in the initiation phase. The fatigue crack growth rates are then quantified using Paris law type equations and linear elastic fracture mechanics (LEFM).

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1. Introduction

Woven fabric composites are being used as primary structural parts in several aeronautical applications. Due to weight reduction, the skin of such structures is often thin and a through-the-thickness crack can appear over the period of service. This macro-crack may be due to defects during manufacturing process, impact or stress concentration. To assess the damage tolerance of such structures with a through-the-thickness crack under fatigue loading, it is thus necessary to characterize the fatigue crack propagation.

These structures are subjected to complex loading conditions but the tension–tension cyclic loading seems to be the worst in term of crack propagation. Some authors investigated the fatigue crack propagation in glass fibre reinforced polymer. Pegoretti et al. [1] studied fatigue crack growth behaviour of polypropylene composites reinforced with short glass fibres and examined how the crack growth varied with fibre content and frequency of the sinusoidal applied load. Experiments were conducted on a single-edge notched tension specimen at room temperature. It was observed that the crack growth rate decreased as the crack length increased in the early stage of the fatigue test. A Paris type law was identified in using strain energy release rate amplitude. Shindo et al. [2] examined the room temperature and low temperatures fatigue behaviour of notched plain woven glass laminates under mode I loading. For all specimens, the weft fibre bundles were aligned with the load axis. Load control fatigue tests were performed with Compact Tension specimens and additionally SEM observations of the crack were performed. Crack lengths were calculated from the compliance data obtained during test using finite element analysis. Three stages of fatigue crack growth were identified: crack initiation, stable crack growth and unstable crack propagation. Optical micrograph of fatigue crack path taken at approximately $N/N_f = 90\%$ showed an amount of damage near the crack tip especially at low temperatures. The damage zone consisted of matrix cracks in the undulation region. Therefore, as the size scale of damage that occurred was not small compared to the other significant dimensions, J-integral was used and the crack growth rate was related to ΔJ through a power law relationship.

However, few works were conducted on relatively thin laminates. The objective of this work is to describe the fatigue propagation of a through-the-thickness crack in notched laminates made of two woven glass plies aligned with the load direction. The influence of the tows nature (warp or weft) of the woven ply on the crack growth is studied and the crack initiation duration influence on the propagation law coefficients is evaluated.

2. Material and experimental details

The material used in this research is glass/epoxy woven composite. The studied laminates are made of two 8-harness satin balanced woven fabric (8-HS) pre-pegs plies with a fibre volume fraction of 50%. The two plies are aligned with the load direction and two kinds of laminates are studied whereas warp or weft tows are in tension. The stacking sequence is $[0/90]_2$. To initiate a through-the-thickness crack, the test specimen is notched with a 0.2 mm diameter diamond thread. The fatigue tests are conducted in strain control at room temperature (about 20 °C) at a frequency

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doi:10.1016/j.ijfatigue.2009.01.010

of 20 Hz. The imposed strain levels are $\varepsilon_{min} = 10^{-3}$ and $\varepsilon_{max} = 3 \times 10^{-3}$. This maximum fatigue strain level corresponds to the infinite life asymptote in *S–N* curve [3–7] and is widely used as design fatigue strain for structures made of glass plies. The specimen is cooled down to room temperature by a fan and its temperature is monitored (the thermocouple sensor is located 10 mm under the notch). No increase in temperature was recorded.

The skins of aeronautical structures are often constrained to spar strain. To represent the real loading conditions, a test specimen with an unidirectional carbon fibres strip on one edge has been developed. Moreover, it reduces the likelihood that global inelastic strains occur under fatigue loading. The characteristics of the test specimen are summarized in Fig. 1. The stacking sequence of woven laminate is $[0/90]_2$.

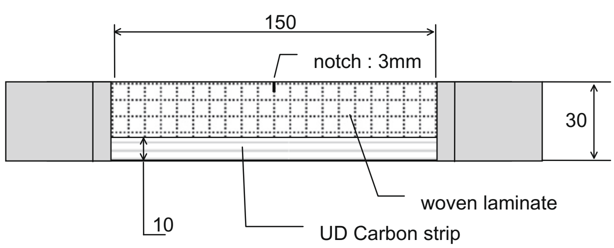

Fig. 1. Fatigue test specimen characteristics.

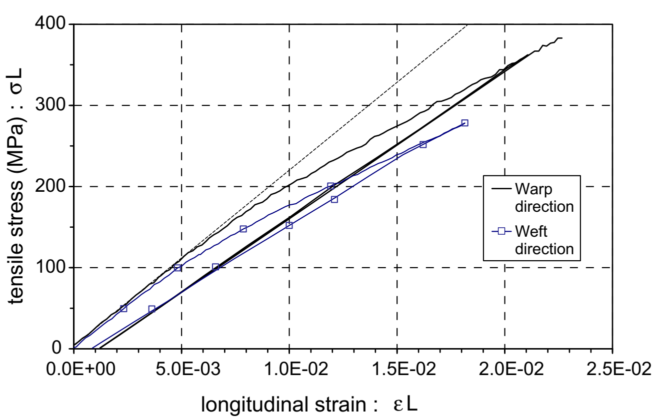

Fig. 2. Stress–strain curves of warp and weft direction $[0/90]_2$ glass woven laminates.

Fatigue tests are performed on a INSTRON 10 kN closed-loop servo-hydraulic tension machine with an extensometer with a 50 mm gage length on the carbon strip to control strain level. The crack growth is monitored with the help of a CCD camera. Due to the relative transparency of the glass fibres reinforced plastics, the propagation of a white damage zone by back-illumination is observed. This kind of phenomenon was also described by [5,8].

The microscopic examinations reveal the presence of fibre tows breakage and through-the-thickness crack all along the damage zone (Fig. 3). In front of the damage zone, the microstructure is safe. As [4,6,9] stated, it is observed that tows breakage occur preferentially in the crimp zones.

First, the static mechanical properties of the woven glass material are given in Table 1. The woven ply is balanced and the tensile elastic modulus for both warp and weft directions are approximately equal. The ultimate tensile strength is influenced by the tow type: weft direction is more undulated and knee-point in this direction is earlier than warp one (Fig. 2). The warp tow is considered to run straighter than weft one.

The tensile behaviour curves of both warp and weft directions are shown in Fig. 2. The warp direction being straighter than the weft one results in a greater ultimate tensile stress. Finally, inelastic strains appear with high stress conditions as the unloading paths previous to failure show.

3. Results and discussion

Fatigue crack propagation in thin woven laminates of stacking sequence $[0/90]_2$ is influenced by the tow type. The crack growth is first analysed in laminates with warp tows in tension and next in weft laminates. The crack length corresponds to the white damage zone length; the microscopic study shows that tows breakage and through-the-thickness crack exist all along the damage zone.

3.1. Fatigue crack growth in the warp direction

Fig. 5 presents crack growth versus cycles for warp laminates. Due to specimens width and notch length, the maximum crack length is around 17 mm. In accordance with previous results [1,2,10], crack propagation starts from the “initiation” phase (sometimes called “stage I”): crack length does not exceed 2 mm and the crack growth rate is slow. Then it continues with the “propagation” phase of stage II (where the Paris law is supposed to hold) where the rate is important up to the last stage where the carbon strip influence leads to crack arrest. The main fact underlined by these results is the large dispersion between sam-

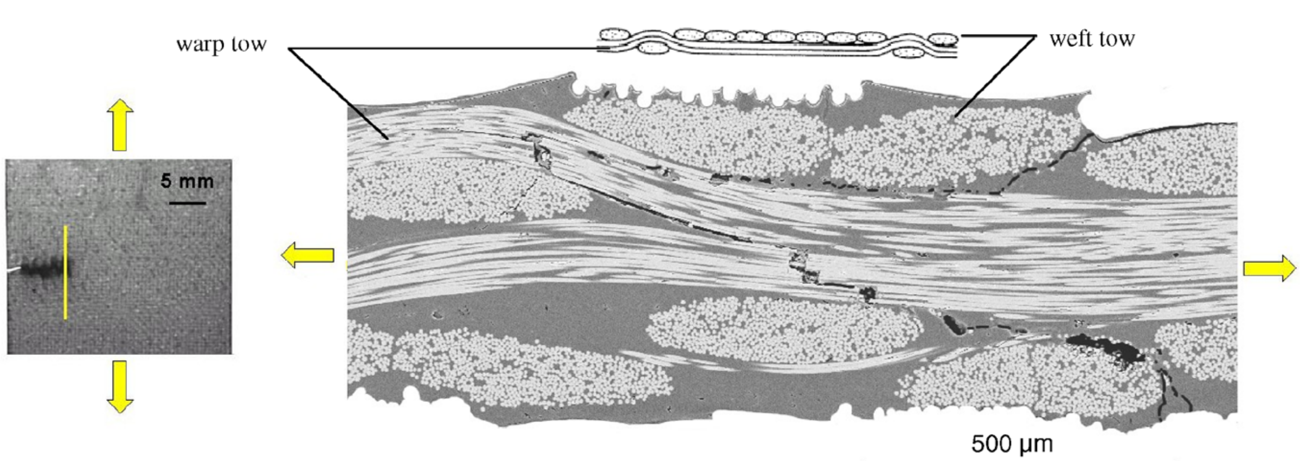

Fig. 3. Through-the-thickness crack and tow breakage in the tip of the visible damage zone.

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