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Fatigue crack growth in thin notched woven glass composites under tensile loading. Part I: Experimental

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ABSTRACT

Helicopter blades are made of composite materials mainly loaded in fatigue and have normally relatively thin skins. A through-the-thickness crack could appear in these skins. The aim of this study is to characterize the through-the-thickness crack propagation due to fatigue in thin woven glass fabric laminates. A technological test specimen is developed to get closer to the real loading conditions acting on these structures. An experimental campaign is undertaken which allows evaluating crack growth rates in several laminates. The crack path is linked through microscopic investigations to specify damage in woven plies. Crack initiation duration influence on experimental results is also underlined.

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1. Introduction

Woven composites are advanced materials that are commonly used in aerospace applications. Their use is interesting owing to their excellent drapability over complex geometries, their effective manufacturing cost and their good damage tolerance properties.

For example, the skin of helicopter blades is often made of a few woven plies (Fig. 1). In these thin structure parts, a through-the-thickness crack might appear in service; such a crack could initiate and propagate from existing defects caused by manufacturing processes, stress concentration or low-energy impact [1]. In order to anticipate such a scenario which could slightly modify the rotor dynamic behaviour, it seems useful to study the crack propagation in these skins in fatigue. Blade loads are mainly defined by centrifugal forces and flap and drag bending moments due to cyclic aerodynamic loads. These structures are therefore subjected to fatigue stresses where the primary load is tension due to centrifugal effects.

Few studies are available related to fatigue crack propagation in woven laminates. Mandell [2] studied the propagation of a through-the-thickness crack in notched specimens loaded in tension–tension fatigue ($R = 0.1$, $f = 4$–7 Hz). Laminates were made of polyester resin and glass woven plies lined up with the load direction. The thickness was about 2.5 mm and the initial notch was cut with a 0.63 mm thickness diamond saw. The main characteristic underlined was that the crack growth was linked to fibre tow width. Moreover, difficulty was encountered in measuring the crack length because of the stepwise nature of the crack growth and the extensive damage region associated with the crack tip. More recently, Shindo et al. [3] examined the mode I fatigue behaviour of notched plain woven glass laminates. For all specimens, the weft fibre bundles were aligned with the load axis. Load control fatigue tests were performed on CT specimens of thickness 25 mm. 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. The damage zone consisted especially of matrix cracks in the fibre bundle undulation region. Furthermore, the size scale of damage that occurred around the crack tip was not negligible compared to the other significant dimensions. Pegoretti and Ricco [4] investigated fatigue crack growth in polypropylene composites reinforced with short glass fibres. Experiments were conducted on a single-edge notched tension specimen of width 27 mm and of thickness 2.7 mm at room temperature: the notch length measured was 3 mm. The crack growth rate level was found to decrease as the fibre weight fraction increased. A further analysis of the data indicated that crack propagation was also governed by viscoelastic creep. Other works merely focused on the experimental determination of the fracture toughness of thin quasi-isotropic laminates made of glass woven plies in single edge notch (SEN) of center notch (CNT) specimens loaded in tension [5,6]. Constant values of fracture toughness are found for different crack lengths.

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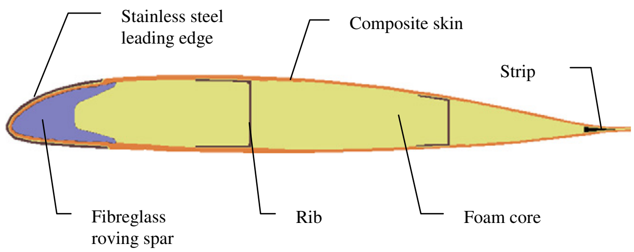

Fig. 1. Typical helicopter blade section.

The objective of this present paper is to study the tension–tension fatigue propagation of a through-the-thickness crack in notched laminates made of few woven glass plies. Several laminate stacking sequences are used for skin blades but some directions are commonly used. Thus, three simple stacking sequences are considered:

- An orthotropic laminate $[0]_2$ with two glass woven plies lined up with the tensile load. The influence of the tows nature (warp or weft) of the woven ply on the crack growth is supplemented. The fibre fatigue behaviour influence on the crack growth is then evaluated. In this paper, the laminate with the warp yarns of woven plies in the tensile direction is noted $[0°]_2$ and actually presents 50% of fibres in 0° and in 90° directions; similarly, the laminate with the weft yarns in the tensile direction will be noted $[90°]_2$ and presents 50% of fibres in 0° and in 90° directions.
- A bias laminate $[45]_2$. This laminate exhibits an important non-linear behaviour in tension. In this regard, the influence of matrix fatigue behaviour on the crack growth is assessed. It can be noted that this laminate presents the warp yarns in 45° direction and the weft ones in −45° direction, and in fact presents 50% of fibres in 45° and in −45° directions.
- A "quasi-isotropic" laminate [45; 0; 45] with a middle woven ply having warp fibres in the load direction. This one may present coupled phenomena of the two previous laminates. Basically, this laminate is not quasi-isotropic, because quasi-isotropic needs the same number of plies in each direction, but this term is still used in the text below in order to simplify notations and is in quotes to avoid confusion.

2. Fatigue test specimen

The crack propagation is studied in glass/epoxy woven composite. These laminates are made of 8-harness satin balanced woven fabric (8-HS) pre-pegs plies with a fibre volume fraction of 50%. The yarn size is 0.5 mm-width and 0.1 mm-thickness. The elastic modulus are 21.5 and 20.5 GPa, the limit strength 385 and 280 MPa, respectively in the warp and weft directions, the shear modulus is 3.5 GPa and the shear strength 65 MPa. The samples are always manufactured with the warp woven face on the top of the thickness, so the top face is a warp side and the underside face a weft one.

In analyzing a typical blade section (Fig. 1), it can be stated that the skin has to follow the longitudinal strain of the spar mainly loaded by centrifugal effect. This remark leads to the development of a technological fatigue test specimen (Fig. 2) having a width 50 mm. A severe notch is performed on one edge with a 0.2 mm diameter diamond thread to limit the through-the-thickness crack initiation duration. On the other edge, a strip of T300/914 unidirectional carbon fibres having a stacking sequence of $[0]_2$ is placed to get closer to the real loading conditions and plays the role of spar. It also reduces the likelihood of global inelastic strains occuring

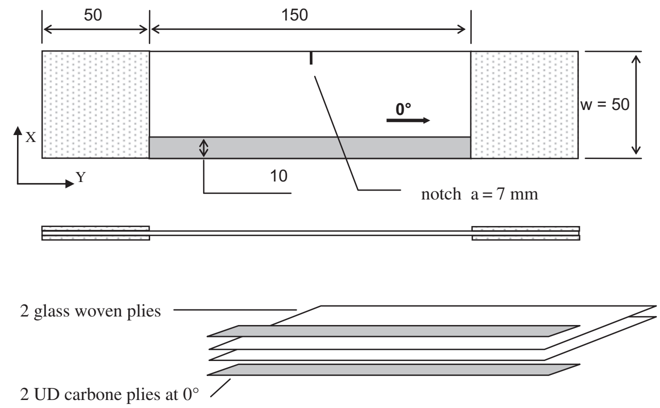

Fig. 2. Fatigue specimen test characteristics.

under fatigue loading. The fatigue tests are conducted under strain control at room temperature (about 20 °C) on a 100 kN closed-loop servo-hydraulic Instron tension machine, with an extensometer placed on the carbon strip, at a frequency 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 [7–11] 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 saved (the thermocouple sensor is located 10 mm under the notch). Furthermore, no increase in temperature was recorded.

The crack growth is monitored with the help of a CCD camera (Fig. 3). The different devices are driven with the help of a Labview program. 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 [5,9]. In a previous work [12], this damage zone was identified as a through-the-thickness crack all along by microscopic investigations. Since the beginning of the crack growth, this damage zone has presented tows breakage even in the tip. This damage zone also contains transverse yarn cracking and meta-delaminations [13].

3. Fatigue crack growth results

3.1. Warp and weft direction

Earlier experiments [12] showed a different behaviour between warp and weft directions of the studied balanced woven ply under static loading as well as in fatigue, especially in crack propagation tests in samples of 30 mm width (Fig. 4). The main fact underlined by these results is the large dispersion between samples in both cases, either for the laminates with warp tows coinciding with load direction, or for the weft ones. It can be noted on this figure, the six warp and weft samples are exactly the same, only the initial crack tip position relative to the yarns should be different (this manufacturing parameter is difficult to control). These differences have been connected to the crack initiation time [12] which depends on the sollicitation direction and on the initial crack tip position relative to the yarns position. In fact, more the initiation time is long, more the crack growth decreases because of the extended of the damage zone. This fact may be due to the small number of plies [14] and perhaps because the experiments are led in strain controlled. Moreover, the crack growth initiation duration in warp laminates was lower than in weft laminates. As the weft direction undulation is more severe, the matrix damage in this direction appears sooner. So, the initiation phase lasts more and the crack growth rate decreases because of the extended damage zone.

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