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Fatigue damage accumulation in notched woven-ply thermoplastic and thermoset laminates at high-temperature: Influence of matrix ductility and fatigue life prediction

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ABSTRACT

This work was aimed at investigating the influence of matrix ductility on the high-temperature tensile fatigue behaviour in notched and unnotched C/PPS (thermoplastic) and C/Epoxy (thermoset) laminates. Damage mechanisms and overstress accommodation near the hole have been discussed by means of X-rays observations and fractography analysis. In order to quantitatively evaluate the fatigue damage within notched and unnotched laminates as a function of the cycles, a damage variable based on a mean strain calculated on each cycle from the experimental stress–strain loops has been used. Finally, a simple analytical model was applied to test its predictive capabilities to evaluate the fatigue damage accumulation in both materials. This model proved to be relevant to predict the evolution of fatigue damage in notched C/PPS composites but not in C/Epoxy laminates.

1. Introduction

1.1. Background

Notch sensitivity of composite materials depends on the ability of a material to accommodate overstresses near the hole [1]. To evaluate the possible advantages of using a tough thermoplastic (TP) resin as a matrix in a notched composite material, many authors have compared the monotonic and fatigue behaviour of TP-based and thermosetting (TS)-based laminates, as it was first addressed 20 years ago [2–6]. Since then, it is known that the ability of a material to accommodate overstresses near the hole at room temperature is less effective in C/TP than in C/Epoxy laminates, due to less degree of stress relieving damage formation around the notch [7]. The effects of matrix ductility and toughness on notched/unnotched carbon woven-ply laminates has been studied in [1,8]: the failure mechanisms of C/Epoxy laminates are exclusively governed by progressive delamination from notch tips, whereas no appreciable effects are observed on the notch tip fracture of C/TP laminates. As temperature increases, the mechanisms of overstresses accommodation are more complex [9,10]. More specifically, a preliminary work was done to understand how the behaviour of polyphenylenesulfide (PPS) high performance TP matrix contributes to the fatigue behaviour of PPS-based laminates at temperatures higher than their glass transition temperature [11–13]. It turns out that both ductile and time-dependent behaviours of polymer matrix are instrumental in ruling the fatigue response of woven-ply PMCs thanks to the presence of matrix-rich regions which proved to play a significant role [14]. The present work was aimed at investigating the contribution of matrix ductility to the tension–tension fatigue behaviours of notched TP- and TS-based laminates at test temperatures T such as: $T_g|_{C/PPS} < T < T_g|_{Epoxy}$. Through a comparison with the fatigue behaviours of unnotched laminates consisting of the same materials, the effect of ductility on both fatigue behaviour and life time has been discussed, particularly at elevated temperature as matrix ductility is exacerbated. In order to quantitatively evaluate the fatigue damage as a function of the cycles, a damage variable based on a mean strain calculated on each cycle has been used. Finally, a simple analytical model was applied to test its predictive capabilities to evaluate the fatigue damage accumulation in both materials [15].

1.2. About the fatigue behaviour of notched laminates in polymer matrix composites

Notches are known to improve the fatigue behaviour of TS-based laminates because damages around the notch may

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induce a local relaxation of stresses [16–19]. Damage onset and growth near the hole are different in PEEK-based and Epoxy-based laminates [20–28]. Damage is widespread around the hole in TS-based composites, whereas it is localized in TP-based composites [4,5]. The experimental observations reported in literature indicated that fatigue damage in C/Epoxy laminates consists of a combination of matrix cracks, longitudinal splitting and delamination which attenuate the stress concentration and suppress fibre fracture in the notch vicinity; as a consequence, fatigue failure can be reached only after very high numbers of cycles while tensile residual strengths continuously increase over the range of lives investigated (10^3–10^6 cycles). Due to the superior matrix toughness and the high fibre–matrix adhesion, the nature of fatigue damage in C/PEEK laminates strongly depends on the stress level. At high stresses the absence of early splitting and delamination promotes the propagation of fibre fracture therefore resulting in poor fatigue performances and significant strength reductions; while at low stress levels damage modes are matrix controlled, similar to those of C/Epoxy laminates, ultimately resulting in very long fatigue lives. As compared to the brittle system, the superior matrix toughness and ductility of the C/PEEK system act as a delay to matrix damage growth. As a consequence, it degrades the fatigue performance and the residual properties of notched configurations when cycled at high stress levels [16]. The importance of the early phases of loading is evident from the observation of the two drastically different damage patterns; at stress levels near the transition threshold, even small variations in local material properties (zones of statistically weak or misaligned fibres, imperfect fibre–matrix adhesion, drilling or manufacturing defects, etc.) can play, during the first cycles, a crucial role by favoring each of the two competing damage modes which control subsequent material behaviour.

2. Materials and experimental set-up

2.1. Materials

The studied composite materials (see Table 1) are carbon fabric reinforced laminates consisting of two different matrices [1]: a semi-crystalline high-performance PPS (TP) and an amorphous Epoxy one (TS). The toughened PPS resin (Fortron 0214) and the epoxy resin (914) are respectively supplied by the Ticona and by Hexcel. The woven-ply prepreg, supplied by SOFICAR, consists of 5-harness satin weave carbon fibre fabrics (T300 3K 5HS). The volume fraction of fibres is 50% in C/PPS and C/Epoxy laminates. A DMTA analysis showed that the glass transition temperature is 95 °C in C/PPS, whereas it is 190 °C in C/Epoxy. The prepreg plates are hot pressed according to an angle-ply $[(\pm 45)]_7$. The fabric is balanced in warp and weft directions such as each ply consists of the same mass fraction of fibres oriented at +45° (warp direction), and at −45° (weft direction). The notched and unnotched test specimens were cut by water jet from $600 * 600\ \text{mm}^2$ plates (see Fig. 1). The central circular hole has a 3.2 mm diameter.

Table 1
Mechanical properties of $[0]_7$ laminates at room temperature [1].

	C/Epoxy	C/PPS
E_1 (GPa)	63.3	56.5
E_2 (GPa)	63.3	56.5
G_{12} (GPa)	5.29	4.08
ν_{12}	0.04	0.04
σ_1 (MPa)	690	700
σ_2 (MPa)	690	700
σ_{12} (MPa)	116	115

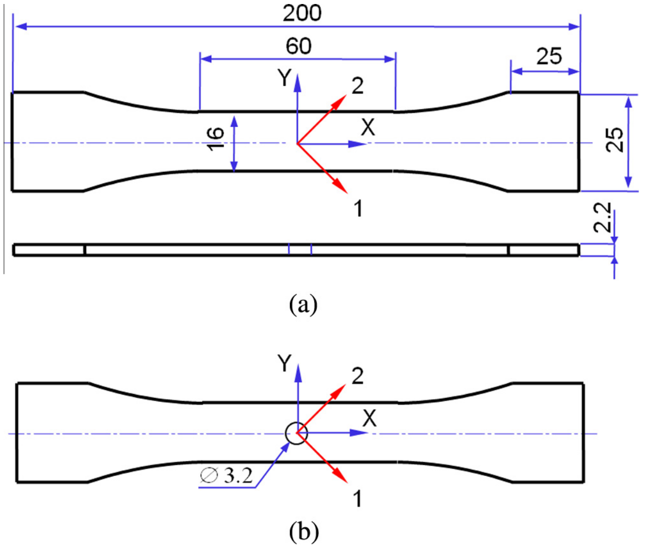

Fig. 1. Dimensions and geometry of fatigue specimens: (a) unnotched and (b) notched.

2.2. Method

All the fatigue tests were performed using a 100 kN capacity load cell of an MTS 810 servo-hydraulic testing machine at room moisture, at constant crosshead speed applied to the specimen during stress-controlled tests. The temperature control system (oven and temperature controller) provided a stable temperature environment during the test. Fatigue tension–tension tests were conducted at 10 Hz, and at three stress levels: 50%, 60% and 70% of σ_{ult}. All tests were performed at an expected ratio $R = 0$, and at a test temperature equal to 120 °C. Such a temperature was chosen because advanced aeronautics structures, and particularly nacelles require high-performance fibre-reinforced polymer matrix composites, which can be used at temperatures up to about 120 °C. During fatigue tests, longitudinal strains were measured with an extensometer (gage length $l_0 = 25$ mm). Three specimens were tested in each configuration. Due to limitation in time, fatigue tests were stopped after 1 million cycles. In addition, a fractography analysis (Scanning Electron Microscope observations of failed specimens) was conducted in order to understand the fatigue damage mechanisms specific to each material. SEM investigations were performed with a LEO 1530 Gemini ZEISS microscope.

3. Results and discussion

3.1. Influence of notches and matrix nature on the macroscopic fatigue behaviour

As it was observed in [5], the tension–tension fatigue behaviour of both materials is characterised by longitudinal stress–strain loops whose shape is different from one material to the other: a “banana” shaped loop in C/PPS laminates, and an elongated ellipse shaped loop in C/Epoxy laminates. However, the area and the inclination of the loops depend on the applied stress level, and the matrix nature (see Fig. 2). Indeed, it can be observed on stress–strain curves that the energy losses are represented by hysteresis loops whose shape clearly depends on matrix nature. C/PPS laminates display “banana” shaped loops consisting of two parts. The first part is associated with the loading phase during which the large rotation of fibres comes along with the large plastic deformation of PPS matrix (strains at failure ranging from 8% to 20%). The second part is associated with the unloading phase during which