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Effect of fatigue loading rate on lifespan and temperature of tailored blank C/PPS thermoplastic composite

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ABSTRACT

This article reports an experimental investigation of the effects of the loading frequency on the temperature change, fatigue behaviour, and failure mechanisms of carbon-fibre-fabric-reinforced polyphenylenesulphide (PPS) laminates, the thicknesses of which were varied by ply drops. The experiments specifically considered two ply drop configurations and fatigue loading frequencies of 0.5–15 Hz. Fractographic examination revealed the presence of loading-frequency-based surface fracture features in the tested specimens. With increasing loading frequency, the local temperature also increases significantly, reaching as high as above 110 °C, accompanied by more than one order of magnitude decrease in the fatigue life. For a surface temperature of up to 38 °C, there was no specific relationship with the fatigue life. However, further increase of the surface temperature up to and beyond 75 °C was accompanied by significant reduction of the fatigue life. An analytic relationship between the load rate and the local temperature was derived and used to define limits for the fatigue testing of tailored blank structures.

1. Introduction

Thermoplastic matrix composites (TPMCs) are increasingly being used for the fabrication of airframes in the aerospace industry owing to their superior resistance to impact damage [1] and better formability [2] compared with conventional epoxy-based laminates. The recyclability of TPMCs [3] is another significant advantage from the perspective of environmental conservation. The large-scale use of TPMCs was previously hindered by the complex manufacturing process and high cost. New technologies have, however, been used to significantly overcome these drawbacks, with large amounts of the materials presently ordered by manufacturers. TPMCs are specifically used as constant-thickness materials for the construction of the primary airframe components. A wide range of thermoplastic resins is available for their production, such as polyetheretherketone (PEEK) and polyphenylenesulphide (PPS), which are among the most widely used high-performance thermoplastic (TP) resins [4]. The present study focused on the mechanical behaviour of carbon/PPS (C/PPS) composites.

Compared to thermosets, thermoplastic matrices can be produced by different technologies that not only enable better exploitation of the mechanical properties of the matrices, but also significant weight reduction. Typical advanced technologies that are employed in the current fabrication of airframes include hot forming using 'tailored blanks'. The use of tailored blank technology facilitates the variation of the composite thickness, fibre orientation, composition, and shape in accordance with the specific requirements. The technology is particularly used when the composite thickness needs to be varied within a single component to maintain the strength with reduced weight. However, a number of the material and structural parameters required for the numerical evaluation that is necessary for this purpose have not been sufficiently investigated. These included the fatigue parameters, temperature, and ageing of the parts of varying thickness can be ranked among these parameters.

1.1. Effect of temperature

At a high temperature, the nonlinear behaviour of fibre-reinforced composites becomes significant [5–11]. A nonlinear response is associated with the shear deformation of the polymer matrix along the reinforcement fibres. The pronouncement of this behaviour at high temperatures is due to the viscoplastic nature of the TP matrix [11–14]. Few studies have considered the behaviour of carbon-fibre-fabric-reinforced PPS laminates or the effect of a high temperature on the behaviour of UD-reinforced PPS matrices [8,14–21]. With regard to the mechanical properties of notched and un-notched laminates, a service temperature higher than the glass transition temperature of a C/PPS composite (i.e., T_g = 98 °C) does not seem to significantly affect the strength or stiffness of quasi-isotropic laminates, whereas it severely

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degrades the mechanical properties of angle-ply laminates [14]. It has actually been established that temperature is the environmental conditioning factor that is most detrimental to the fatigue properties of a laminate [17].

It is generally accepted that C/PPS-reinforced thermoplastic materials have high static and fatigue strengths. However, this is not the case under certain conditions of temperature and moisture. Aircrafts operate under different temperature and humidity conditions, and the hygrothermal ageing of a utilised composite may alter the glass transition temperature and lead to a significant decrease in the mechanical strength and ultimate strain [22]. Several researchers [23–26] have investigated the detrimental effects of ageing, and the effect of moisture has also been shown to be less severe than that of temperature [27–30].

1.2. Fatigue loading of thermoplastic matrix composites

Fatigue loading is one of the main types of loading of structural elements, and it is capable of causing catastrophic failure under certain conditions. However, the fatigue response of C/PPS thermoplastics, especially those with varying thickness and ply drops, has not been sufficiently investigated. Indeed, there is a need for extensive experimental studies in this area. Continuous-fibre-reinforced composites are characterised by the development and accumulation of several types of defects including matrix cracking between the fibres, delamination between adjacent plies, debonding between the matrix and fibres, and fibre fracture. Such defects in a composite system are not isolated but interconnected. The identification of existing crack paths is thus a highly complex task. Moreover, most of the defects occur long before the ultimate failure of the component, and many types of subcritical failures may thus occur [22,31–33].

In the case of matrix-dominated composites, the fatigue behaviour is significantly controlled by the behaviour of the polymer matrix. Polymers do not exhibit the equivalent of the crystallographic stage I crack propagation observed in metals, for which reason crack initiation is the most important stage in the fatigue life of a polymer [34]. Conversely, polymers experience two types of failures, namely, cyclic creep failure and thermal failure, which occur under certain combinations of loading conditions. Cyclic creep occurs under conditions of sufficiently high loads and low frequencies [35], while thermal failure occurs at high frequencies, which prevent the dissipation of the energy loss due to the inherent high damping of the polymer. This results in a significant increase in temperature, which in turn induces thermal softening and loss of property [29,31,36–40].

1.3. Effect of loading frequency

As the role of the matrix becomes more dominant, there is an increase in the viscoelastic effect on the time-dependent properties in the entire composite. For this reason, and considering the nature of fatigue loading, the loading frequency is assumed to be one of the most important factors that affect the fatigue behaviour of such materials.

Fatigue failure associated with large-scale hysteretic heating has been observed in polymers [37] and glass-reinforced epoxy [38], with the fatigue life decreasing with increasing loading frequency. The effect of hysteretic heating is less severe in graphite/epoxy composites, in which case the fatigue life increases with increasing loading frequency when temperature increase during the fatigue test is small (temperature rise lower than 10 °C) [41]. A similar trend has been observed in the case of boron-epoxy composites [36]. Several studies on the fatigue behaviour of AS4 PEEK have shown that the effect of hysteretic heating on the composite is much more pronounced than in the case of thermoset composites [29,36,37], and that the fatigue life significantly decreases with increasing loading frequency. Generally, the temperature of the composite tends to stabilise at a certain value after a certain number of cycles, and this equilibrium temperature also increases with increasing load level or loading frequency. The main parameters that affect the equilibrium temperature include the friction between damaged sites and the heat accumulation due to the poor thermal conductivity of the material. In some cases, the material fails under fatigue long before reaching the equilibrium temperature.

Nevertheless, the effect of the loading frequency on the fatigue behaviour of an advanced thermoplastic matrix composite requires further investigation. The pronounced viscoelastic nature of the matrix material and the accompanying thermal effect during fatigue loading significantly impact the reliability and mechanical performance of the composite.

1.4. Effect of ply drops

With the aim of weight saving and more uniform stress distribution, it is necessary to decrease the thickness of the less loaded parts of the structure. The details of the loading of an integral structure are determined by the specific type of external load, the centre of mass of the structure, and the location of its neutral axis. Thickness optimisation is an ideal approach to decreasing the weight of a structure. The insertion of semipregs at suitable locations of the structure could be used to facilitate a more uniform stress distribution, as well as thickness variation. However, such might induce an undesirable temperature increase, which would affect the structure under fatigue loading. The use of ply drops to vary the thickness may be classified as an external, an internal (longitudinal or transverse), or a mid-plane ply drop construction [42].

However, problems may arise from the use of ply drops (inserted ply ends) because the resultant stress concentrations could induce damage [42,43]. Helmy et al. [44] investigated the tensile fatigue behaviour of internal ply drops and observed that the fatigue cracks were initiated near the ply drops and propagated along the interface to the thicker section through a mode II propagation. According to Wisnom et al. [45], asymmetry does not appear to be a critical factor of this type of delamination. The fatigue life of a ply drop composite is significantly shorter than that of a plain composite mainly because of the initiation and growth of the delamination near a ply drop [46].

To investigate these problems, numerical models based on global-local approaches have been developed using Timoschnecko beam elements [47] or cohesive zone elements with the Hashin and LaRC failure theories [48]. Nevertheless, to gain a deeper understanding of the fatigue behaviour of a composite component with varying thickness, an extensive experimental program is required, such as that used for the certification of airframes, parts, and materials. Time and cost are the main considerations in such material and structural certification processes, and this necessitates the use of higher loading frequencies to conduct fatigue tests. Thickness variations in a component also constitute stress concentrators that may affect the durability of the component under the increased temperature induced by an applied cyclic load.

This paper describes an experimental investigation of an asymmetrically tapered laminate with internal ply drops loaded under tension-tension fatigue conditions. The objective of the study was to acquire data for designing and determining the fatigue strength of a rib demonstrator and to define the load rate limitation that must be considered during the certification of experimental materials and structural parts. Additional data was collected for the development of new models for conducting fatigue degradation simulations.

2. Materials and methods

2.1. Material configurations and parameters

The stacking and thickness variations of the rib used for the experiments of the present study corresponded to those of a real structure, namely, the rib of a large aerospace structure [49,50]. The laminate thickness varied between 3.4 and 5 mm. The plates were fabricated from carbon-fibre fabric prepreg according to AIMS 05-09-002 [51]