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Influence of matrix nature on the post-fire mechanical behaviour of notched polymer-based composite structures for high temperature applications

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ABSTRACT

This study aims to investigate the influence of matrix nature (thermosetting – epoxy 914; and thermoplastic – Polyphenylene Sulfide PPS) on the tensile thermo-mechanical behaviour of both notched and unnotched laminates. Depending on variable prior fire-exposures, the purpose was to compare the changes on the residual tensile mechanical properties of carbon fibre reinforced epoxy 914- and PPS-based laminates subjected to stress concentration for aeronautical purposes (e.g., at service temperatures higher than glass transition temperature, T_g). With respect to the unnotched laminates, the area of the hole is an open access through the thickness for the heat flux causing more or less thermal degradation (depending on matrix nature) and resulting in variably decreasing the laminate tensile properties. Surprisingly, a low heat flux leads to virtually no decrease in the residual tensile strength of PPS-based laminates; however, in epoxy 914-based composites, the exposure to a low heat flux is more detrimental as exposure time is long. Fractography analyses were performed to investigate damage mechanisms in perforated laminates. The influence of fire-induced damages, the subsequent degradation of the mechanical properties due to fire exposure, combined with the overstresses near the hole all contribute to significantly decrease both stiffness and strength of C/epoxy notched laminates. In notched C/PPS laminates, the fire-induced degradation, resulting from the redistribution of melted PPS matrix within the fibre network, may compete with a relaxation effect in the overstressed 0° carbon fibres in the vicinity of the hole. These competing mechanisms are expected to reduce the influence of fire-exposure on the residual tensile strength of notched C/PPS laminates.

1. Introduction

1.1. Background

A major disadvantage of polymer matrix composites (PMCs) is poor performance in fire, which is of the utmost importance for applications in aerostructures. The behaviour of PMCs in fire has been a major concern for over thirty years and much effort has been devoted to investigate their behaviour in fire and assessing their residual mechanical properties [1]. The behaviour of composite materials in fire is largely governed by the chemical nature and processes involved in the thermal decomposition of the polymer matrix as well as in the organic fibres. A great number of different polymers are used in composites but the chemical nature and decomposition behaviour of the thermoset (TS) polymers and thermoplastics (TP) most commonly used in composites are reviewed here. C/epoxy composites were extensively used in aeronautics for the past 40 years but they are characterised by many engineering drawbacks, including: low-temperature storage, very long autoclave time, handmade draping, manufacturing issues, poor impact resistance, low damage tolerance and poor fire resistance. Hence, the initial concept of this work was to determine whether it is possible to replace a thermoset matrix (Epoxy) with a TP matrix (Polyphenylene Sulphide (PPS)) in carbon-fibre reinforced PMCs and whether this can be practically applied in nacelles of plane's engines. With the service temperature of these structures being elevated (e.g., 120 °C), the question was to evaluate how detrimental prior fire-exposure can be on the high-temperature tensile behaviour of PPS-based laminates compared with epoxy-based laminates [2,3]. TP-based composites usually have higher

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post-fire properties [1–4]. More specifically, fire resistance defines the ability of a material or structure to impede the spread of fire and retain mechanical integrity [1,2]. Fire resistance also describes the ability of a construction to retain structural integrity (i.e., shape, load-bearing properties) in a fire. Following these definitions, the main fire resistant properties are heat insulation, burn-through resistance and structural integrity. Mechanical integrity is another important fire resistant property that defines the ability of a material or structure to retain mechanical properties such as stiffness, creep resistance and strength when exposed to fire and after the fire has been extinguished. Assessing the structural integrity of composites in a fire is still largely reliant on experimental testing. Although no standardised experimental technique exists, various methods were developed to evaluate the loading capacity of composite structures in fire [4–8]. Experimental data needed to assess the survivability of composite structures are extremely limited as conducting tests to determine their performance under blast, shock, ballistic and fire conditions is time consuming and expensive [1].

There is a lack of experimental data for high gradient composite structures (e.g., perforated laminates) in the literature, especially in critical service conditions such as fire exposure. Indeed, many composite structures contain thousands of holes for joining purposes and open cutouts for access [9]. The development of stress concentrations in composite structures remains of great concern and many studies investigated the effect of holes on strength [9–19]. The complex damage and failure mechanisms present during the loading stage in a composite laminate are increased due to the presence of a stress concentration, causing a wide range of effects, such as stress or strain gradients, not observed in unnotched components. The influence of stress concentrators on the thermo-mechanical behaviour of composite structures depends on the ability of a material to accommodate overstresses near the hole. This is closely associated with matrix nature as it implies specific damage mechanisms in TS and TP composites [13–21], which appear to be highly temperature dependent [17–19]. Therefore the role played by the matrix in the distribution of overstresses is essential and the issue remains to determine how detrimental the matrix thermal degradation near the hole affects the accommodation of overstresses in perforated structures.

1.2. Objectives of the study

There is a need to investigate the influence of a prior fire exposure on the residual mechanical properties of carbon fibre reinforced TS- and TP-based composites subjected to stress concentration at elevated temperature, for applications in aeronautics (e.g., at service temperatures higher than glass transition temperature, T_g). In notched laminates, holes provide open access for the heat flux, which can significantly contribute to the degradation of the laminates through the thickness. Thus, the influence of fire is expected to be more detrimental on the residual mechanical properties of notched laminates compared with unnotched laminates. Before considering the influence of high heat fluxes on the thermo-mechanical behaviour, this study aimed to determine a trend on the effect of low heat fluxes (e.g., 20 kW/m^2) for different fire-exposure times (from 2 to 5 min) on the mechanical properties and failure modes in perforated quasi-isotropic laminates subjected to tensile loadings at high temperature (e.g., 120 °C), depending on matrix nature (amorphous thermoset or semi-crystalline thermoplastic). Such testing conditions are assumed to be representative of the heat flux produced in the early stage of a nacelle's fire [20]. Finally, a fractography analysis was conducted to investigate the influence of fire-exposure on tensile damage mechanisms in perforated laminates.

2. Materials and method

2.1. Materials and specimens

The composite materials studied in this work consist of seven ply carbon fabric-reinforced PPS or epoxy prepreg laminate plates [2]. The semi-crystalline PPS resin (Fortron 0214) and the epoxy resin (914) are supplied by the Ticona and by the Hexcel Companies, respectively. The woven-ply prepreg, supplied by the SOFICAR Company, consists of 5-harness satin weave carbon fibre fabrics (T300 3K 5HS). The mass fraction of fibres is 58% in both materials. The prepreg plates are hot pressed into quasi-isotropic laminates [(0.90)/(±45)/(0.90)/(±45)/(0.90)/(±45)/(0.90)] according to the processing conditions specified in Fig. 1. The notched and unnotched test specimens were cut by water jet from 600 × 600 mm^2 plates (Fig. 2). The central circular hole has a 3.2 mm diameter, such that the width-over-hole diameter ratio is equal to 5. The machining of the holes may have a significant influence on potential damages near the hole. Using a twist drill can cause several types of defect in fibre-reinforced polymer-matrix composites [22]. In the present case, holes were drilled by means of a diamond tool (drill bit), which is known to minimise damage near the hole [23].

The average thickness (calculated from five measurements each) of consolidated specimens is virtually constant in both materials: 2.22 ± 0.2 mm in C/PPS laminates and 2.20 ± 0.1 mm in C/Epoxy laminates. In virgin C/PPS laminates, the glass transition temperature is $T_g = 98$ °C, the crystallinity rate is equal to 30%, and $T_g = 190$ °C in C/Epoxy laminates [2,3].

2.2. Experimental set-up and methods

2.2.1. Fire exposure tests

The experimental set up of fire exposure tests is previously described in Refs. [2,3]. To reproduce the effect of fire, many studies use the radiant heater of a cone calorimeter to burn composite specimens [24,25]. Using this heating method, the heat flux and the heating conditions are controlled and repeatable; however, the exposure to a cone calorimeter represents an idealised fire condition (i.e., it is a stable and involves a continuous fire with no convective heat transfer from the heat source to the specimen). In addition, only a small area of specimen can be burnt with this a fire-exposure test method. A heat flux meter can be used to calibrate the cone calorimeter and to control the heat flux on the specimen surface. Low heat fluxes (e.g., 20 kW/m^2) were applied to both notched and unnotched specimens for different exposure times (2 or 5 min). After fire-exposure, all the specimens were cooled in the air for one night. The "virgin" state chosen for comparison purposes represents the state of specimens exposed to no prior fire. Three specimens were tested in each configuration.

2.2.2. Thermo-mechanical tests

The service temperature of engine nacelles is 120 °C. It is therefore necessary to perform tests at $T > T_g$ for C/PPS and $T < T_g$ for C/Epoxy laminates. The tensile tests were performed on notched and unnotched laminates using a 100 kN capacity load cell of an MTS 810 servo-hydraulic testing machine at constant crosshead speed applied to the specimen during displacement-controlled tests. The temperature control system provided a stable temperature environment during the test. The tensile mechanical properties were determined according to the European standards EN 6035 [26]. For both notched and unnotched laminates, the longitudinal modulus (E_X) and ultimate strength (σ^u) were calculated from the following definitions: