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Influence of stamping on the compressive behavior and the damage mechanisms of C/PEEK laminates bolted joints under severe conditions

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ABSTRACT

Bolted joint tests have been performed in order to evaluate the influence of stamping on the behavior of thermoplastic-based woven-ply laminates subjected to structural loadings under severe service conditions (120 °C after hygrothermal aging). Compressive tests have been carried out on carbon fabrics reinforced PolyEtherEtherKetone (PEEK) laminates to investigate fibers buckling due to changes induced by stamping on the non-planar interply structure of woven-ply laminates. As compressive strength decreases by 13% in stamped laminates, it facilitates the plastic buckling of 0° and ±45° oriented fibers due to compressive loads in bolted joints. Contrary to double-lap joints, stamping does not affect the strength of single-lap joints, as the geometry of single-lap joints is non-symmetric. Stamping modifies the damage mechanisms of PEEK-based laminates under bolt-bearing loadings, such as the failure of stamped bolted joints is dominated by bearing failure mode.

1. Introduction

1.1. Background

When it comes to innovate in aeronautics, a material choice is a key point as it must comply with three main requirements: weight/price/certification. The use of high-performance thermoplastic (TP) polymers is a growing material trend in the fiber reinforced polymer industry, and the progression of TP resins from secondary to primary structure in aeronautics (e.g. A380 wing fixed leading edge or parts of aircraft engine's nacelles) is opening up the design and manufacturing envelope with a new set of production characteristics [1]. More specifically, many parts of nacelles can be manufactured from stamped fiber-reinforced TP composite materials [2–5], which are expected to be used under severe service conditions (120 °C after hygrothermal aging — HA). Hygrothermal aging refers to the process in which the deterioration of the mechanical performance and integrity of composite materials results from the combined action of moisture and temperature. In carbon fiber reinforced composites, moisture absorption and diffusion occur at the fiber–matrix interface, which affect its cohesion. From the brief review proposed in Refs. [2–4], hot/wet conditions seem to be even more detrimental that test temperature is high. As TP-based composites largely retain their mechanical properties under severe conditions, it seems relevant to consider for applications in severe environments [3–7]. In this context, this study consisted of two parts whose purpose was to evaluate the influence of stamping on PolyEtherEtherKetone (PEEK)-based composites to be used in aircraft engine nacelles. The first part was aimed at addressing the influence of stamping on mechanical performance (tensile, in-plane shear and inter-laminar shear) of fabric reinforced thermoplastic laminates under severe conditions [5]. The effects of processing have been discussed at different levels: influence on the micro-structure (porosity and mean free path) and meso-structure (reinforcement and matrix distribution), changes in the matrix properties as well as in the fiber/matrix interface. The obtained results and the Scanning Electron Miscroscope (SEM) observations suggest that these changes are closely associated with the macroscopic mechanical behavior of laminates. According to the conclusions drawn in this previous work, stamping proved to

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be a re-consolidation process, and the high stamping pressure promotes two primary mechanisms: re-compaction of the fiber network and migration of melted matrix. These mechanisms significantly influence the meso-structure properties (better interlaminar adhesion and fiber/matrix bonding), resulting in the overall improvement of the material properties. In addition to basic testing (tensile, inplane shear, interlaminar shear), there is a need to perform structural tests (e.g. tensile tests on bolted joints) on TP-based laminates in order to qualify them for aeronautical purposes under severe service conditions [5,6].

1.2. Objectives of the study

Composite structures are usually joined with bolts or rivets in different geometrical configurations, such as single-bolt single lap joint and single-bolt double lap joint tests (see Fig. 1). In bolted joints, the load is transferred from one structure to the other via the bolt [8], and usually leads to specific damage mechanisms [9], depending on matrix nature [10]. Investigations have been carried out recently on the long-term behavior of bolted joints consisting of textile TP composites for which the reinforcement architecture also appear to play a role [11]. The purpose of the present work was to provide an insight into the behavior of TP-based woven-ply bolted joints under service conditions (120 °C after HA), but also to emphasize the correlation between compressive and bolted joint responses at high temperature when matrix ductility is enhanced.

2. Material and methods

2.1. Materials and specimens

The composite materials studied in this work are carbon fabric reinforced PEEK prepreg laminate plates supplied by the Porcher Company and referenced as 3106-P17 PEEK Pi preg [5,6]. The woven ply prepreg laminate consists of 5-Harness Satin (HS) weave carbon fiber fabrics in a PEEK resin matrix (Grade 150 supplied by the Victrex Company). The volume fraction of carbon fibers is 50% and the mass fraction is 57%. The carbon fiber fabrics, referenced as T300 3K 5HS, were supplied by the Soficar company. The influence of stamping on the thermo-mechanical behavior of PEEK-based laminates has been evaluated on consolidated and stamped specimens obtained from thermo-compression whose processing conditions are given in Ref. [5]. In the present case, the shape of the parts obtained from stamping and consolidation is a flat panel, hence justifying that stamping occurs without any major fiber reorientation. Compressive test specimens were obtained from orthotropic plates $[(0,90)]_7$, whereas bolted joint specimens were obtained according to quasi-isotropic lay-ups. All specimens were sawn from 600 × 600 mm plates with a water-cooled diamond saw. The average thickness t (from 5 measurements each) of specimens is virtually constant (See Table 1).

2.2. Experimental set-up and methods

Prior to mechanical testing, all the specimens were exposed to hot-wet aging for 1000 h in the following environment: 85% of relative humidity and 70 °C. An MTS 810 servo-hydraulic testing machine equipped with a 100 kN capacity load cell has been used to perform quasi-static tests at room moisture, and at a test temperature equal to 120 °C. Compressive, single-bolt double lap and single-bolt single-lap joint tests have been conducted on aged specimens. The mechanical properties were determined according to the standards presented in Table 2 [12,13]. In Table 2, L and w denote the length and width of the specimen, respectively, and d represents hole's diameter. V denotes constant crosshead speed (in mm/min) applied to specimens. Four specimens were tested in each configuration. The values, reported in Table 3 and Table 4, have been averaged from the results obtained for each specimen. Lastly, a fractography analysis was performed by means of an Olympus optical microscope or SEM investigations (LEO 1530 Gemini ZEISS microscope). A Dynamic Mechanical Thermal Analysis (DMTA) provides the glass transition temperature T_g of C/PEEK laminates: $T_g = 145$ °C in consolidated materials, and $T_g = 150$ °C in stamped materials [5].

3. Results and discussion

3.1. Compressive tests

3.1.1. Compressive behavior and damage mechanisms

The compressive behavior plays an important role in the response of C/PEEK bolted joints because the 0° and ±45° oriented fiber bundles are mainly subjected to compressive loads [5] as it can be observed on Fig. 5. The compressive strength is commonly obtained from the relationship $\sigma^u_{XX} = F^u/t.w$ defined in Ref. [12]. Even though the compressive modulus is unchanged, the compressive strength decreases (−13%) in stamped laminates. The laminates responses to compressive loadings are characterized by an elastic/brittle behavior in stamped specimens, whereas the behavior seems to be elastic/ductile with a sudden failure in consolidated specimens (see Fig. 2). The compressive response is different in consolidated and stamped laminates, as their failure mode significantly depends on the meso-structure changes [5]. The compressive failure is usually governed by three primary mechanisms in composite laminates [14]: (i) transverse shearing leading to the fragmentation of the external plies. Such a mechanism is mostly based on the breakage of 90° fibers, and proved to be relatively stable [15] – (ii) splaying of external plies is associated with a longitudinal splitting between 0° fibers bundles. The breakage of 0° and 90° fibers occurs to a lesser extent in relation to the fragmentation mode. The friction between plies plays an important role in promoting splaying – (iii) local buckling of 0° fiber bundles coming along with a plastic deformation of the

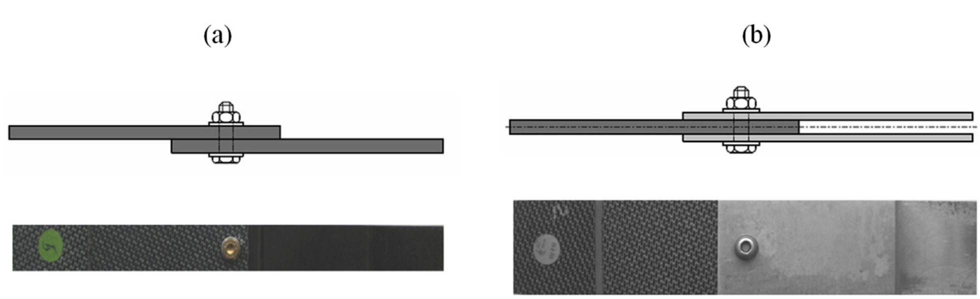

Fig. 1. Schematic representation of bolted joint specimens [9]: (a) Single-bolt single lap – (b) single-bolt double lap.