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Compression after impact and fatigue of reconsolidated fiber-reinforced thermoplastic matrix solid composite laminate

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Abstract

Carbon fiber-reinforced poly-phenylene sulfide laminate coupons were impacted at low-energy in a drop-tower machine and subsequently fatigued in a four-point bending fixture. The doubly damaged test pieces were then hot-press reconsolidated and inspected nondestructively by vibrothermography to check their structural integrity. The residual mechanical properties of the laminate in both the as-damaged and as-repaired conditions were determined by compression loading with the in-plane strain fields determined via a digital image correlation system. Cross-section views of damaged and repaired samples were analyzed by light optical microscopy and correlated to residual mechanical properties, as were the digital image correlation and nondestructive test results. Based on the values of stiffness and ultimate strength of the repaired laminates, 10 J was inferred as the maximum impact energy at which it is worthwhile performing hot-press reconsolidation, in view of the applied fatigue history following impact.

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Keywords: Compression after impact and fatigue; damage tolerance; digital image correlation; repair of fiber-reinforced thermoplastic composite; vibrothermography.

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1. Introduction

The use of continuous carbon fiber-reinforcing thermoplastic matrix composite laminates in secondary and primary structural members of commercial jet aircrafts has been increasing steadily in the last decade (Dias and Rubio, 2003). Two of the most attractive characteristics of thermoplastic composite materials are their reparability and damage tolerance (Shin and Wang, 2002; Wang and Shin, 2002). Therefore, it is vital to determine not only their potential for reconsolidation by hot pressing after they are impact damaged and subsequently fatigue loaded, but also, and to the same extent, their after-repair ability in withstanding mechanical loads.

In this work, high-performance continuous carbon (C) fiber-reinforced PPS (poly-phenylene sulfide) thermoplastic matrix coupons were low-velocity impacted in a drop-weight tower system and subsequently fatigued in a four-point bending fixture. The PPS-C coupons were then hot-press reconsolidated and inspected nondestructively by vibrothermography (sonic infrared thermography, or thermosonics) to ascertain their structural integrity. After that, their post-damage and after-repair residual mechanical properties were determined by in-plane compression testing, which were periodically recorded via a 2D digital image correlation (DIC) system to map strain-fields developed over the full test piece surface. A microstructural analysis was performed of cross-sectioned samples extracted from damaged and reconsolidated PPS-C test pieces via light microscopy to assess the conditions of the polymer matrix and reinforcing fiber to correlate them to results obtained from mechanical tests, as were the DIC and nondestructive inspection techniques.

2. Material and test coupons

Sixteen plies of 0/90° bidirectional 5-harness satin 3K T300 JB continuous carbon fiber fabric semi-impregnated with poly-phenylene sulfide (PPS) thermoplastic resin were piled-up in a quasi-isotropic ply arrangement $[(0/90),(+45/-45)_2,(0/90)]_4$ and hot-pressed at ~330°C to obtain a 5 mm-thick PPS-C flat laminates composed of 50% of fiber volume content. Rectangular test coupons with in-plane dimensions of (150 x 100) mm^2 were machined using a water-refrigerated diamond cut-off wheel.

3. Experimental setups and procedures

3.1. Impact test

PPS-C coupons were transversally impacted in a drop-tower testing machine. Single-impact loading with 10, 20 or 30 J of energy was applied to a set of test pieces using an impactor with a 16-mm-diameter spherical steel tip, following the guidelines of the ASTM-D7136 standard (2007).

3.2. Fatigue test

Previously impacted PPS-C coupons were fatigue-tested in a four-point bending system assembled in a servohydraulic testing machine. A maximum compressive stress of 360 MPa, corresponding to 80% of the ultimate flexural strength of a 50 J-impacted test coupon, was applied to the specimen at a stress ratio of 6 and frequency of 4 Hz during 5.5 10^4 cycles to simulate one operational fatigue lifespan, as per Brazilian aircraft industry protocol. The test set-up and experimental guidelines of the ASTM-D7264 standard (2007) were used.

3.3. Hot-press repair

Impacted and subsequently fatigued PPS-C coupons were sandwiched between flat metal molds and slowly heated under an inert gas atmosphere (N_2) in a resistance furnace until a processing temperature of 330°C was reached. The molds containing pre-damaged coupons were then removed from the furnace and pressed between water-cooled plates.

The heating and cooling rates, as well as the pressure applied during reconsolidation/repair of the impaired PPS-C coupons, strictly followed the procedures described by Costa *et al*. (2008) for hot-compression manufacturing of full-scale PPS-C demonstrator products devised for Brazilian aircraft.