



Environmentally assisted crack growth in adhesively bonded composite joints



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ARTICLE INFO

Article history:

Received 6 March 2017

Received in revised form 17 August 2017

Accepted 19 August 2017

Available online 26 August 2017

Keywords:

Debonding

Environmental degradation

Fracture toughness

Joints/joining

ABSTRACT

Adhesively bonding composite components is a reliable alternative to conventional joining processes that minimizes part weight and reduces fabrication costs. Regarding performance and reliability, of particular interest is developing adherend surface treatments that enhance adhesion of the joint interfaces in aggressive chemical environments. Using fracture mechanics-based adhesion metrologies, critical and subcritical crack growth were evaluated for several peel-ply-treated, adhesively bonded composite joints. Fracture toughness, G_c , and corresponding failure modes were evaluated for specimens constructed using two different bonding processes (co-bonding and secondary bonding) and four different peel ply treatments. Environmentally assisted crack growth was evaluated as a function of time in several environments: humid, high temperature humid, and hydraulic fluid immersion. It is shown that humid environments accelerate crack growth rates, da/dt , relative to the strain energy release rate, G . This effect was amplified at elevated temperatures and further amplified in the presence of hydraulic fluid.

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1. Introduction

As lightweight composites replace conventional monolithic materials in structural engineering applications, there is a growing need for reliable yet cost effective methods to join composite components. This is of particular concern in the aviation industry where advanced polymer composites are increasingly being integrated in aircraft designs to reduce weight and boost fuel efficiency [1–3]. Unlike metals, composites often cannot be joined by welding or brazing, and though reliable, mechanical fastening (e.g. bolting or riveting) adds undesired weight and can induce damage (i.e., cracking or delamination near rivet holes) [4,5]. Adhesive bonding processes, however, are appealing alternatives as they tend to minimize weight and machining costs, transmit forces with limited stress concentrations [6–8], and resist corrosion [1,6].

In order to promote strong, durable bonds the surfaces of polymer composites may be modified through mechanical or chemical treatments, which promote wettability [9–11], increase projected bonding area [12], and create regions of newly exposed bulk material devoid of atmospheric contaminants [9,13,14]. While sanding, grit blasting, etching, and plasma treatments have been used to

modify surfaces for bonding [9,11,13], the peel ply method provides a simple cost effective choice. A peel ply treatment typically involves vacuum compacting a woven fabric composed of low surface energy polymer (the peel ply) onto the surface of a composite such that it becomes impregnated with the polymer matrix material during the cure process. When removed after cure the peel ply fabric leaves a negative imprint on the surface (Fig. 1), which promotes wetting and enhances adhesion of an otherwise poor adherend/adhesive bond [13]. Peel ply layers often render the use of release agents—residues of which may negatively impact joints—unnecessary. Additionally, the peel ply provides interim protection from surface contamination as a component awaits the bonding step in manufacturing processes.

Several factors influence the bond quality of an adhesive joint. The peel ply material (polyester or nylon) influences the wettability of a given adhesive on the treated surface, which in turn can impact adhesion properties of the joint [13]. Additionally, contamination of the treated surface (residual peel ply fibers or other foreign materials) [9,13,15,16] and exposure to moisture prior to bonding [17,18] can severely degrade interfacial adhesion. In general, mechanical performance of the bonded joint is sensitive to both temperature and humidity [7,13,17,19–21]. Absorption of water in the adherend can significantly alter mechanical properties [2,5] and weaken the interface between the matrix and load-bearing fibers [5,22]. Absorption of water in the adhesive can lead

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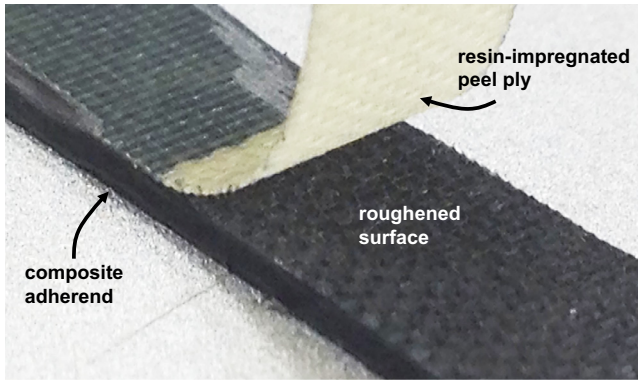


Fig. 1. Image of peel ply fabric partially removed from the surface of a woven fiber composite adherend. Removal of the peel ply generates a roughened surface for enhancing adhesive bonding. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to plasticization and swelling (both of which may manifest as increases in measured toughness), reduced stiffness [5,23], and degradation of the bond at the adhesive/adherend interface [5].

Multiple studies have investigated the strength and toughness of adhesively bonded composite joints [4,6,11,13,16,24], with some focusing on the deleterious role of aggressive environments such as elevated temperature, humidity, or/and contaminants on adhesion [17,18,25–27]. None, however, have investigated the synergistic effects of environmental species (e.g. humidity, hydraulic fluid) on the kinetics of disbonding of peel ply treated joints. Using fracture mechanics-based adhesion metrologies [28–30], an analysis of subcritical crack growth in peel ply treated, adhesively bonded composite joints in humid and wet environments and at elevated temperature is presented. First, fracture toughness, G_c [J/m^2], was evaluated for composite joints constructed using two different bonding processes (co-bonding and secondary bonding) and four different peel ply treatments. Next, environmentally assisted crack growth is subsequently evaluated in several unique environments: humid, high temperature humid, and hydraulic fluid immersion. It is shown that humid environments accelerate crack growth rates, da/dt , relative to the strain energy release rate, G . The effect is amplified at elevated temperatures and further amplified in the presence of aviation hydraulic fluid (Skydrol).

2. Experimental methods

2.1. Materials

Test panel assemblies were fabricated by bonding two carbon fiber reinforced polymer (CFRP) panels together using an epoxy film adhesive. Each panel ($152 \times 381 \times 2.03$ mm) consisted of carbon fibers in a resin matrix (T800H/3900-2, Toray). The layup consisted of eight inner plies of longitudinally oriented

fibers sandwiched between two plies of plain weave fiber (T800H-3900-2, Toray). Bonding surfaces were co-cured with a peel ply fabric as discussed below.

Two adhesive bonding processes - co-bonding and secondary bonding - were evaluated. In the co-bonding process, a pre-cured panel with a peel ply treated surface was bonded to an uncured panel using an epoxy adhesive (AF 555 M, 3 M). The panel cure cycle and the bonding cure cycles were identical, each consisting of a $3^\circ C/min$ ramp up to $179^\circ C$ (held for 120 min) and cooling ramp down at $3^\circ C/min$ to $60^\circ C$, all under full pressurization (6.87 bar (absolute) in autoclave) and vacuum (559 mmHg in a vacuum bag). In the secondary bonding process, two pre-cured composite panels, each with peel ply treated surfaces, were bonded together with an epoxy adhesive (EA 9696, Henkel). The bonding cure cycle was $121^\circ C$ for 90 min under pressure and vacuum. The vacuum was vented to atmosphere when pressure reached 2.39 bar.

For the peel ply surface treatments, a woven polymer fabric (peel ply layer) was co-cured on a composite panel and impregnated with matrix resin during panel cure. Before bonding, the peel ply layers were removed, leaving roughened surfaces consisting of a mixture of fractured matrix and the imprint of the peel ply fabric. A survey of four different peel plies used in aerospace composites was conducted: three composed of polyester—PFG 60001, Diatex 1500EV6, and PFG 60001 coated by the manufacturer with a siloxane release agent to prevent fiber contamination of the treated surface—and one of nylon (PFG Nylon 51789 Style 52006). Of the two polyester variants, PFG 60001 provided a denser fiber imprint than the Diatex. Surface profilometry (Buker Dektak 150 with 10 nm height resolution) was used to characterize roughness of the adherends upon removal of the peel ply fabric. The average surface roughness values (R_a) over $2\text{ mm} \times 2\text{ mm}$ representative areas were 13.5, 13.3, and $12.8\ \mu\text{m}$ for the PFG 60001, Diatex, and PFG Nylon imprints, respectively. Table 1 provides a summary of the several commercial and BMS (Boeing Material Specification) adhesive/peel ply treatments evaluated.

2.2. Specimen preparation

Double cantilever beam (DCB) coupons $12.7\text{ mm wide} \times 152\text{ mm long} \times 4.2\text{ mm thick}$ were cut from the bonded assemblies. Prior to bonding, a 12.7 mm strip of fluorinated ethylene propylene (FEP) film was placed on the peel ply impressed surface of one panel (lengthwise, adjacent to an edge) to serve as a crack starter for DCB testing (Fig. 2). Aluminum loading tabs reinforced with sapphire bearings were bonded to the beams with an adhesive (H20NS, Hysol). Fracture testing at elevated temperature/high humidity required a high temperature adhesive (Aremco 570) to prevent the loading tabs from disbonding. Since the Aremco adhesive cures at $177^\circ C$, which is above the $121^\circ C$ cure of the secondary bond (EA9696) specimens, the tabs were clamped in place then heated locally with a heat gun. Thermocouples were placed along the length of the specimen to ensure the

Table 1
Summary of fracture specimen configurations.

Specimen	Adherend	Bond	Adhesive	Cure ($^\circ F$)	Peel Ply Type	Fabric
CP1	BMS 8-276	Co-bond	AF555M	350	BMS 8-308 Type III	Polyester
CP2	BMS 8-276	Co-bond	AF555M	350	BMS 8-308 Type IV	Polyester
CP3	BMS 8-276	Co-bond	AF555M	350	BMS 8-308 Type III (siloxane)	Polyester
CN1	BMS 8-276	Co-bond	AF555M	350	Nylon 5789 Style 52006	Nylon
SP1	BMS 8-276	Secondary	EA9696	250	BMS 8-308 Type III	Polyester
SP2	BMS 8-276	Secondary	EA9696	250	BMS 8-308 Type IV	Polyester
SP3	BMS 8-276	Secondary	EA9696	250	BMS 8-308 Type III (siloxane)	Polyester
SN1	BMS 8-276	Secondary	EA9696	250	Nylon 5789 Style 52006	Nylon

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