Chapter 6

Investigation of Failure in Unidirectional Adhesively-Bonded Composite Joints via Infrared Thermography

Nithinkumar Manoharan and Suhasini Gururaja

Abstract Adhesive bonding is one of the most effective methods for joining composite materials, preferred over mechanical bonding due to its significant advantages such as reduced weight and uniform stress distribution. Adhesively bonded composite joints are widely used in high cycle fatigue (HCF) applications, including aircraft and wind turbines. While extensive research has been focused on the fatigue performance and failure modes of lap joints due to their ease of manufacturing, it is critical to investigate the fatigue behavior of fully bonded adhesive joints. In lap joints, under cyclic loads, shear and peel stresses are well-studied for their role in damage initiation due to the load path. However, in fully bonded adhesive joints, uniaxial stress across the multi-material system presents various challenges, such as the adhesive-adherend interaction along the longer bondlines. Therefore, understanding the location of damage initiation, the evolution of damage mechanisms, the factors influencing failure, and the failure mode are essential.

This study aims to use infrared thermography (IRT) to evaluate the behavior of fully bonded unidirectional glass fiber-reinforced polymer (UD-GFRP) composite adhesive joints under quasi-static tensile and fatigue loading. The in situ full-field surface temperature variations during cyclic and static loading are recorded using a cooled infrared camera and examined in addition to the displacement field data obtained by two-dimensional digital image correlation (2D-DIC) data to assess damage incipience and progression. Additionally, the recorded surface temperature data is analyzed in the frequency domain to detect second harmonic signals, which are associated with dissipative heat sources and serve as indicators of damage onset and propagation. Pixel-wise analysis of second harmonic signal data provides a visual representation of damage evolution.

Keywords Adhesive bonding · Infrared thermography · Unidirectional glass fiber-reinforced polymer · Digital image correlation · Quasi-static tensile loading

Introduction

In recent decades, composites have become integral to various industries due to their lightweight properties and superior mechanical performance compared to metals. While this adoption continues to grow, the manufacturing of composite materials presents challenges such as high cost, maintenance difficulties, and complex repair processes. Additionally, joining composite structures for assembly and functionality remains a critical manufacturing step. Mechanical joining remains predominant in several industries due to several advantages such as ease of accessibility and repair. However, composite materials face unique challenges with mechanical fastening, such as machining damage, and high stress concentrations at the location of holes drilled for fasteners which could significantly compromise the mechanical performance. Adhesive bonding, on the other hand, requires relatively minimal surface preparation and provides uniform stress distribution while enabling joining of dissimilar materials [1]. As a result of this, huge structures such as wind turbine blades use adhesively bonded interfaces. Despite these advantages, adhesively bonded composite joints are sensitive to manufacturing defects such as trapped voids in the adhesive layer and non-uniform bonding of the adherend-adhesive interface. Such bondline defects could cause localized vulnerable areas that are prone to failure. Delamination and debonding due to the presence of defects have been the leading cause of premature failure in wind turbines after installation [2].

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Thus, it is vital to understand the damage initiation and progression in such multi-material systems to improve the reliability of adhesive joints. This study aims to understand the behavior of UD-GFRP adhesive joints under quasistatic loading. The full field temperature behavior at the adhesive-adherend interface was observed until the final failure. This was then coupled with full-field strain data using 2D-DIC data to assess the failure mode. To further examine the influence of bondline defects, process defects were introduced during manufacturing for a comparative analysis of variations in temperature and strain in the presence of defects.

Background

IRT is a non-destructive and non-contact technique that has gained a lot of attention in recent decades for inspection and analyzing the damage state of the material [3]. This technique is based on the full field surface temperature measurements to observe its variation with applied excitation, either mechanical or thermal. In isotropic materials, the relationship between stress state and temperature variation in adiabatic and elastic conditions is given by the experimental equation for thermoelasticity,

$$\frac{\Delta T}{T_0} = \frac{-\lambda}{\rho C_p} \Delta\sigma \tag{1}$$

where
T_0 – absolute temperature of the material,
ΔT – change in temperature,
λ – linear thermal expansion coefficient,
ρ – material density,
C_p – specific heat at constant pressure,
$\Delta\sigma$ – change in the sum of principal stresses.

The equation 1 was extended to orthotropic materials, such as polymer composites, by introducing thermoelastic constants in each direction [4]. Under tensile loads, composites show an initial decrease in surface temperature due to the increase in volume in the elastic stage, followed by a gradual increase in temperature with damage onset and propagation. IRT has been used as a technique to visualize damage in composite materials by detecting subtle surface temperature changes, which result from internal damage mechanisms such as matrix cracking, fiber breakage, and delamination. The technique has also been pursued by several authors due to its rapid nature of evaluating the fatigue limit with fewer specimens compared to traditional approaches such as stress life (S-N curve) approach [5]. Passive IRT has been used in this study to detect localized damage progression at the adhesive-adherend interface under static loading.

The DIC technique, developed in the 1980s, has been predominantly used across several industries to measure displacement and strains in a broad range of materials including composites [6]. DIC has also been used to characterize multi-material systems, such as hybrid composite-metal joints [7], demonstrating its applicability to sophisticated engineering problems. To understand the tensile behavior of UD-GFRP joints and to analyze the localized deformation in the adhesive-adherend interface 2D-DIC has been used in this study along with passive IRT.

Material and Methods

Unidirectional glass fiber (UD-GFRP ET 1200-7P) from Vectorply Corporation was used as the adherend system in this study, reinforced with 635 Thin Epoxy and Hardener (3:1) from US Composites. A hot press was used to fabricate the laminates at 80 °C with a pressure of 0.5 tonnes for 30 minutes. The adhesive system consisted of MGS PR 135G3/BPH 1355G resin/hardener adhesive bond paste with a weight ratio of 45:100, mixed using a FlackTek SpeedMixer. This adhesive system is similar to those used in wind turbine blade manufacturing [8]. The laminates were cut to the standard (ASTM D3039) using a WAZER desktop waterjet cutting machine, and an aluminum mold was used for the fabrication of the adhesive joint to ensure precise alignment. The adherends were placed at the bottom mold followed by prepared adhesive bond paste uniformly spread over the adherend using a plastic syringe. Finally, another set of adherends was placed at the top and the mold was tightly closed. The protrusions at the top part of the mold ensured uniform adhesive thickness (2 mm) throughout. The mold was placed in an oven at 75°C for four hours for curing. After curing, the specimens were removed, excess adhesive was polished off, and finally, end tabs were placed. In the case of specimens with process defects, a 20 mm long PTFE Kapton film (25.4 um thick) was fixed to the adherend surface, centered along its length, before applying the adhesive to simulate a bondline defect.

Static tests at 1.3 mm/min loading rate (ASTM D897) were carried out using a Landmark MTS servo-hydraulic system (Model 370.10). A cooled MWIR infrared camera (Telops) with a 50 mm lens, 640x512 pixels resolution and 20 mK NETD was used to record the full-field surface temperature at the adhesive-adherend interfaces. The specimen face from which the specimen temperature was recorded was painted black to ensure homogenous emissivity [9]. In order to perform 2D-DIC analysis, the opposing face was painted white with a random black speckle pattern. Images were captured using a Canon EOS Rebel T7i (18-135 mm lens) and later analyzed using Vic-2D (Correlated Solutions) software.

Results and Discussion

The failure load was 29.76 kN in pristine specimens, while the presence of a bondline defect showed an ∼8% reduction in failure load with varying failure mode, not much difference was observed in the failure strain values for both cases. The full field strain field (as microstrains), in addition to the thermograms showing damage initiation and final failure, can be seen in Figure 1. It should be noted that image subtraction was performed using the initial undamaged image as a reference

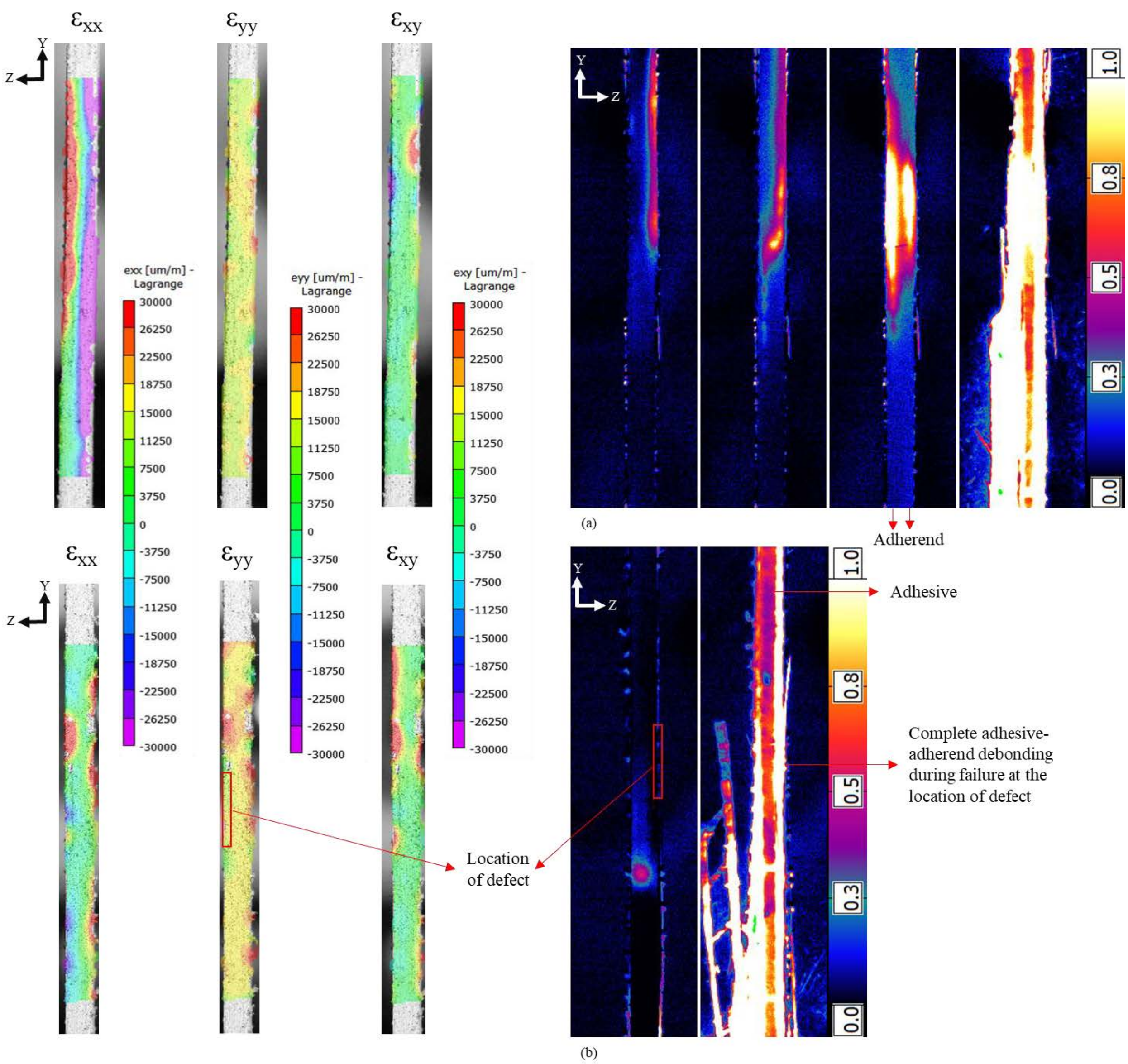

Fig. 1 Full field microstrains before final failure and the thermograms showing change in surface temperature during failure (in °C) after image subtraction with initial state for (a) pristine, and (b) specimen with bondline defect under quasistatic tensile load

to improve the visibility of subtle temperature variations. Pristine specimens and specimens with bondline defect exhibited similar surface temperature behavior throughout the test, where the initial stages of loading showed a decrease in the surface temperature due to the thermoelastic effect, followed by a gradual increase as an indication of damage initiation, and a sudden spike (approximately 20°C in both configurations) during final failure.

The speckle pattern shown clearly distinguishes the adhesive layer from the adherend on either side. The transverse strain (ε_{xx}) field showed a uniform distribution across each layer in pristine specimens, whereas a high strain concentration around the location of defect was seen in the other configuration indicating stress localization. Similar trends were seen when comparing the longitudinal strain (ε_{yy}) contours, where a uniform strain distribution with high values of strain at the location of crack initiation could be seen in pristine specimens, suggesting a more progressive failure, while early stress redistribution around the location of the defect was observed in the defective specimen, leading to a sudden failure [10]. Shear strains (ε_{xy}) showed high values at the interface region where the defect was placed, aligning with a complete interface debond with catastrophic failure at the same location (as seen in the thermograms).

A relatively uniform strain field, with uniform gradual damage accumulation leading to final failure with crack progression from the interface through the adhesive layer causing final failure via crack propagation was observed in pristine specimens. In contrast, specimens with bondline defects showed a non-uniform strain field with localized damage, resulting in sudden, catastrophic failure, highlighting the detrimental effects of even a small defect in the bondline.

Conclusions and Future Work

2D-DIC and surface temperature behavior of adhesively bonded UD-GFRP specimens under quasi-static tensile loads were analyzed. A clear distinction in the full-field strain and temperature behavior was observed, and the combined data provided insight into failure mode in the presence and absence of process defects. The severity of bondline defects was evident, leading to sudden failure and a reduction in final failure load.

Efforts are ongoing to perform cyclic loading on adhesively bonded UD-GFRP specimens. Damage accumulation under fatigue is being studied and the fatigue behavior is evaluated with IRT. The temperature signals throughout the tests are recorded and analyzed in the frequency domain to observe the behavior of the first and the second harmonic components, which have been shown to provide information regarding the damage state of the material [3].

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