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Pulsed phase thermography imaging of fatigue-loaded composite adhesively bonded joints

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ABSTRACT

We applied pulsed phase thermography to image and size damage in adhesively bonded joints. Specifically, the initiation and propagation of fatigue-induced damage in single lap joints with carbon fiber epoxy adherends was investigated. Lap joint specimens with various levels of manufacturing defects were fabricated and loaded in low-cycle fatigue. A calibration specimen with artificial defects was used to design a threshold algorithm for sizing of the damaged regions. The dominant failure mode in specimens without manufacturing defects was fiber-failure, whereas joints failing prematurely demonstrated adhesive failure. Imaging of the lap joints after regular number of fatigue cycles revealed that manufacturing defects could be detected and the resulting, imminent adhesive failure could be identified prior to joint failure. Additionally, the extent of this damage could be accurately estimated through the sizing algorithm. Due to the brittle nature of fiber-failure, it could not be detected prior to failure of the joint, however this was not critical, as the goal was to identify premature failure of the adhesively bonded joint.

1. Introduction

Aerospace vehicle components often demonstrate premature aging during service, such as fatigue cracking and corrosion, which must be detected to ensure their safety. In modern composite airframe materials the critical aging phenomena are often subsurface, presenting new challenges for inspection of aircraft [1]. Once critical inspection location is adhesively bonded joints. Adhesive bonding of multiple composite laminates (adherends) offers substantial advantages over traditional riveting due to their better distribution of stress across the bonded area, low part counts, and high strength to weight ratio of the loading joint region. In addition, adhesive bonding prevents the introduction of free edges at drilled holes, which can later lead to delamination.

However, care must be taken during the fabrication of adhesively bonded joints since environmental conditions and surface preparations can greatly affect the strength and quality of the final bonded joint [2]. Defects appear in two primary regions after manufacturing, within the adhesive layer and at the adherend–adhesive interface [3]. In the adhesive layer, porosity or voids are often caused by air entrapment during the adhesive layup process and cracks can be introduced due to incorrect mixing or thermal shrinkage during cure. Weak bonding or disbonding can also occur at the adherend–adhesive interface due to surface contamination by grease or a loose oxide layer due to poor surface preparation. Such defects often lead to premature failure of the joint before failure of the composite adherends is achieved.

Previous authors have demonstrated that fabrication defects in bonded joints can be easily detected using infrared thermography [4–6]. The detection and sizing of damage in adhesively bonded joints is particularly well captured by thermographic imaging, as the damage plane is typically perpendicular to the thermal wave propagation direction [7,8]. For example, Meola et al. [6] demonstrated that surface roughness, artificial defects and grooves could be imaged in adhesively bonded metallic joints using lock-in thermography. Waugh et al. [4,5] applied PPT for imaging of fabrication defects in adhesively bonded joints, including surface contamination with silicon grease and PTFE inserts. They demonstrated that the PTFE inserts were relatively easy to detect, whereas the silicon grease was only detectable when the joint was under an applied static load, presumably due to opening of the joint during some induced bending. These results highlight the importance of a relatively high thermal contrast between the defect and the surrounding material for successful imaging.

The goal of this paper is to identify whether or not realistic damage modes due to fatigue have sufficient thermal contrast to be observed using infrared thermography. We focus on a small scale representation of an aerospace adhesively bonded lap joint with fatigue damage due to low frequency cyclic loading. In this work, we will apply pulsed phase thermography (PPT) because it can image large sections of an airframe relatively quickly and is therefore a promising technique for commercial aircraft. Other

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thermography methods, such as lock-in thermography or frequency modulated thermography, could similarly be applied with increased spatial resolution, at the cost of increased imaging times.

Prior to imaging of adhesively bonded joints with fatigue induced damage, we calibrate the PPT phase images using a specimen with polymer inserts. As the specimens were manually fabricated, PPT imaging was applied to both specimens that achieved the full fatigue potential of the joints and specimens that showed premature failure due to manufacturing defects.

2. Experimental methods

This section describes the preparation of adhesively bonded lap joint specimens, the low-cycle fatigue loading protocol applied to them and the PPT setup and parameters for imaging of fatigue induced damage.

2.1. Specimen preparation

All carbon fiber reinforced epoxy adherents were fabricated from 8 layers of pre-impregnated 2×2 twill woven carbon fiber (Advanced Composites LTM22/CF0300). Initial laminates were fabricated as 254 mm × 279.4 mm sheets with plies aligned in the 0–90° directions. Prior to the laminate layup, a layer of mylar vacuum bag, two layers of breather ply and a single layer of peel ply were placed on an aluminum plate to prevent excessive resin on the laminate surface. The final assembly was covered by peel ply, breather ply, and finally mylar as the bottom layer. The edge of the vacuum bag was sealed and the air between the two mylar layers drawn out using a vacuum line. An additional aluminum plate was placed on the top and bottom of the mylar sheet to evenly distribute the heat and pressure throughout the curing process. The sample was placed in a hotpress, preheated to 50 °C, and pressurized to a constant pressure of 8.27 MPa. The hotpress temperature was then increased every 15 min by 15 °C until it reached 80 °C. The laminate was then cured for an additional 3 h at 80 °C and then allowed to cool for 12 h at room temperature. Once cured, the laminate was cut into individual pieces using a wet tile saw.

Two different specimen geometries were fabricated: a specimen for calibration of the PPT imaging and lap joint specimens for fatigue loading. The calibration specimen was fabricated from two 252 mm × 101.6 mm panels, as shown in Fig. 1. For this specimen, four artificial defects were introduced, created from various layers of 25.4 mm × 25.4 mm polytetrafluoroethylene (PTFE) tape and a single layer of polypropylene (PP) tape of the same dimensions. Each layer of PTFE tape had a thickness of 0.089 mm. All defects were spaced 38.1 mm from one another. Fig. 1 shows the bottom laminate with the inserts prior to the application of the adhesive layer.

The second specimen geometry followed the ASTM D3165 standard for single lap joint specimens for fatigue testing. The dimensions of these specimens are shown in Fig. 2. This particular single lap joint standard prevents bending of the overlap region during uniaxial loading of the specimen. Bending of the overlap region creates peeling stresses, changing the stress condition from that of an actual structure. In addition, bending would open areas the joint with poor bonding and therefore artificially increase the contrast of thermal images [4,6].

For each specimen, the joining surfaces were prepared by sanding and cleaning each adherend with Al_2O_3 60 grit sand paper and isopropyl alcohol. Hysol EA 9394 epoxy paste adhesive was applied to the adherends and distributed manually, using a steel blade parallel to the surface. The specimens were then placed between two mylar sheets and placed in the hotpress and cured for one hour at 66 °C. The specimens were cooled at room temperature for 24 h.

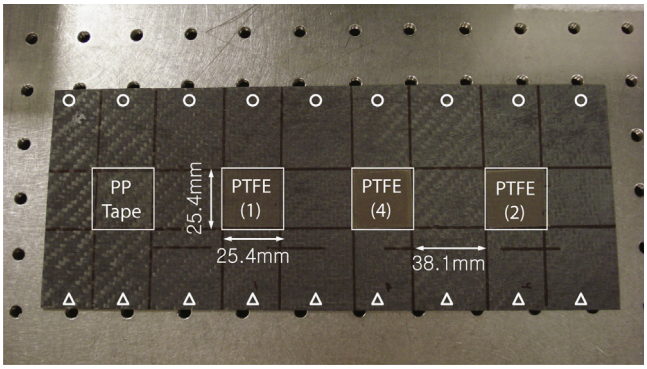

Fig. 1. Location of simulated defects on joining surface of bonded joint. Number of PTFE tape layers is indicated in parentheses. Location of thickness measurements plotted in Fig. 4 is also shown.

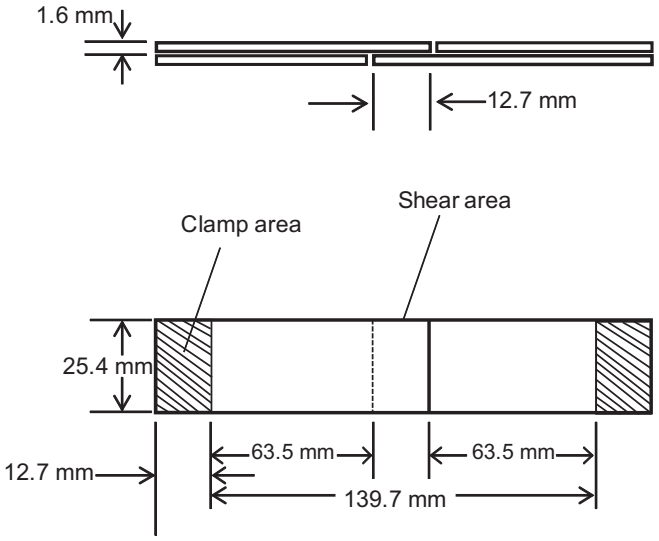

Fig. 2. Dimensions of composite lap joint specimens based on ASTM D3165.

2.2. Fatigue loading

Using an Instron servohydraulic fatigue testing machine, load-controlled, fully reversed cyclic loading was applied to the composite lap joints with a frequency of 3 Hz and in blocks of 200 cycles. The peak-to-peak amplitude of the cyclic loading was determined based on an initial tension to failure test of three lap joint specimens, at a displacement controlled loading rate of 0.5 mm/min. This peak-to-peak amplitude was set at 0.445 kN, approximately 13% of the mean failure load for these three specimens. After each 200 cycle loading block, the lap joint was removed from the fatigue testing machine for pulsed-phase thermography imaging.

A small amount of pre-tensioning was applied to the joint to simulate an in-flight load and the PPT images obtained again. The specimen was then returned to the uniaxial testing machine to continue the fatigue loading. This process was repeated until failure of the lap joint. If the lap joint did not fail after a total of 1000 cycles, the fatigue cycles per loading block were increased to 1000 and the testing continued until specimen failure. After failure of the lap joint, the fracture surfaces were photographed.

2.3. Pulsed phase thermography

Pulsed phase thermography (PPT) applies a square pulse to heat the sample, from which the thermal response at the front surface (in reflection) is decomposed into a multitude of individual thermal waves at different frequencies through Fourier transforms