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An infrared thermoelastic stress analysis investigation of single lap shear joints in continuous and woven carbon/fiber epoxy composites

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ABSTRACT

A full-field thermoelastic stress analysis infrared method is used to study the damage initiation and progression in prepreg uni-tape and woven carbon fiber/epoxy composite single lap joints. Two loading schemes are studied to detect the damage initiation in these joints. In the first scheme the loading is monotonically increased with cyclic loading performed at the holding times. In the second scheme, the loading is increased gradually and then decreased, followed by cyclic loading at the holding time. The thermoelastic stress analysis infrared measurements show that both methods are capable of predicting the onset of damage at the bonded joint. The observed measurements indicate non self-similar crack growth or non-uniform crack extension along the bondline. Microstructural analysis is performed at the locations where damage is believed to have occurred for specimens extracted before final failure. The investigation confirms the capability of this method to capture early stages of damage in bonded joints.

1. Introduction

Engineering aircraft structures with composite materials require a detailed knowledge of durability and damage tolerance of individual structural components, especially in bonded joints due to the importance of initial manufacturing conditions. Issues such as the quality of the adhesive at the time of application, the surface preparation of the adherends, and the final void content are all known to affect the quality of the joint. Traditional mechanical testing methods using extensometers and strain gauges of composite joints may only measure linear load-deformation responses to failure, giving no indication of overload or failure initiation. They are also local measurements that are expensive to install and maintain over long periods of time. Non-destructive full-field real-time evaluation tools offer a significant refinement over traditional mechanical tests, such that failure initiation of critical components can be detected and identified early. Failure progression after initiation of damage in fiber-reinforced polymer joints is not well understood, especially for considerations of fatigue reliability after damage initiation. Different experimental methods and techniques, such as radue life of fiber-riography, photoelasticity, acoustic emission, and thermography, have been applied to investigate the fatigeinforced plastics (FRP). Bakis et al. [1] related the residual strength, stiffness, and fatigue life to corresponding damage states obtained from photoelastic coating and thermal emission experiments for graphite/epoxy laminates subjected to fully reversed fatigue loads. They observed the damage initiated around the hole for quasi-isotropic and orthotropic laminates; they also noted that matrix cracking and delamination patterns were different in both cases due to the interaction between adjacent plies. Compared with photoelastic data, the thermal emission was more sensitive to the minute deformations near the fracture paths in the surface plies. Swain et al. [2] investigated the effect of interleaves on the damage mechanisms and residual strength of notched composite laminates subjected to axial fatigue loading. They described the effect of interleaving in carbon epoxy laminates with normalized stiffness versus normalized life curves by examining residual strength and evaluated delamination by using X-ray radiography and dye-penetration. Although they were able to use traditional methods such as stiffness and strength in a quantitative measure of cumulative damage, the X-ray radiography results showed matrix cracking, delamination, and other damage mechanisms in a qualitative manner. Brien et al. [3,4] investigated damage and failure of angle ply laminated composites at or near the free edge by using X-ray radiography and optical methods. They investigated laminates using 3D Finite Element Analysis (FEA) for each configuration, looking at in-plane shear and transverse normal stresses as indicators of matrix cracks in off-axis plies. Microscopy and X-ray radiography were applied on straight coupons of AS4/350-6 graphite epoxy laminates to qualitatively validate the 3D FEA

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models for load-life fatigue behavior. Using dye-enhanced X-ray radiography and microscopy, Lessard [5] investigated the effect of ply orientation on the initiation and progression of damage for the compress.

Studies have shown that the Thermoelastic Stress Analysis Infrared (TSA-IR) based technique is a powerful tool for evaluating damage in many applications with fiber reinforced polymeric materials. For example, in Dulieu-Smith et al. [6], a T-joint was investigated using TSA and correlated to a finite element analysis. Finger joints in pultruded glass-reinforced plastic (GRP) profiles were also investigated and a calibration process based on the quasi-isotropic surface layer were used [7]. The approach was also applied on a double-butt strap joint configuration of pultruded materials [8]. The results illustrate the potential to use TSA for bonded joint especially if separate calibrations can be obtained for the different regions in the bonded joint. Lin and Rowlands [9] used a complex-variable formulation involving conformal mappings to determine the individual stress components in composites. For damage in composites, Mackin and Roberts [10] tracked static damage progression in ceramic matrix composites using TSA-R on double-edge notched specimens. Bremond and Potet [11] also illustrated the advantages of TSA-IR as a non-destructive method. Kageyama et al. [12] suggested a damage threshold approach based on 3D FEA and used TSA-IR with linear elastic fracture mechanics to measure the crack propagation in notched carbon/epoxy laminates. An IR based method was also proposed and used to track the damage in [$\pm$45] and [0/90] type graphite/epoxy laminates by Lohr et al. [13]. In their experiment, the measured temperature was seen to decrease as the number of cycles increased due to cracking in the epoxy surface layer. El-Hajjar and Haj-Ali [14,15] proposed a technique to measure the sum of the direct strains on the surface of a thick section and orthotropic composites using the TSA-IR signal obtained from the surface of the specimen. Their method was verified experimentally and compared favorably with FE simulations of notched and cracked coupons. This method was used to verify damage studies in thick-section composite materials considered by Kilic and Haj-Ali [16,17]. Several studies have also investigated the use of TSA-IR to evaluate mixed-mode stress intensity factors of anisotropic laminates [15,18]. Wei et al. [19] used TSA-IR with stochastic Markov Chains to characterize the fatigue damage in composite laminates and they proposed a method to predict the S–N curve.

The single lap joint geometry due to the multiaxial stresses generated in the critical areas has been traditionally used to investigate possible changes in design to improve static and fatigue performance. It is also a common design detail in various bonded structures. In many cases FEA is used to investigate the stress distribution differences within the bondline for alternative joint geometries to better understand the effect of geometry on joint performance. For example, Zeng et al. [20] developed a wavy composite lap joint as an alternative to traditional lap joints or adhesive joint geometries with tapered edges to avoid the load eccentricity and the associated singular peel stresses at the joint ends. The wavy lap joint resulted in compressive peel stresses at the joint ends that altered the failure progression so there was no indication of damage initiation before final failure. A comparison of the wavy lap joint with the traditional lap joint showed crack initiation from the load/displacement relationship and visual inspection of cracks. Avila et al. [21] used an FEA method to make correlations between stress distributions in the wavy lap joints and the single lap joints made from E-glass/epoxy composites. They noticed a 41% higher load carrying capacity for the wavy lap joints over the conventional single-lap joints attributed to a more uniform stress field with the existence of compressive normal stresses in the wavy lap joint. Fessel et al. [22] showed significant improvements in overall joint strength for the reverse-bent joint over the traditional lap shear joint for several steel alloy substrates with different overlap lengths. They used FEA to evaluate stress distributions within the bond and discussed potential improvements of joint strength by modifying joint geometries to achieve more uniform stress distributions instead of highly localized stresses at the joint ends. Da Silva and Adams [23] compared basic double lap geometries with an inside tape and adhesive fillet design with various resins using experimentally determined failure loads and FEA to evaluate the internal stress distributions due to combined temperature and mechanical loads using titanium and carbon fiber composites. Campilho et al. [24] investigated joint efficiency using a parametric FEA study of internal stress distributions for different overlap lengths, plate thickness, and stacking sequences of single lap joints. The experimental part of their study focused mostly on ultimate failure stresses of the joints instead of failure initiation. Borsellino et al. [25] showed some evidence of capturing stabilization by investigating changes in failure (adhesive/cohesive) mechanisms with extended curing times as viewed by surface inspections of failed single lap joints. FEA was used to evaluate internal stress distributions, and the experimental evaluation was based on mechanical testing (flexural modulus, ultimate failure stresses, or impact resistance). Cheuk and Tong [26] studied the damage failure modes in lap joints in the presence of precracks. They proposed analytical methods to predict failure using maximum stresses and critical strain energy release rates.

Initial testing results on lap joints using TSA-IR with acoustic emission verifications was presented by Haj-Ali et al. [27] showed how TSA can be an effective technique in determining the onset of damage. In this study, we present an expanded view of their tests and focus on the full-field thermoelastic stress analysis infrared method (TSA-IR), specifically how to interpret the TSA-IR signal showing damage initiation and progression in prepreg uni-tape and woven carbon fiber/epoxy composite single lap joints. Two loading schemes are studied to detect the damage initiation in these joints. Microstructural analysis is performed at the locations where damage is believed to have occurred for specimens before final failure and complete failure of the bondline.

2. Thermoelastic stress analysis method

TSA-IR was applied on composite single lap joints to investigate material behavior in two joint types. The overall goal was to characterize damage evolution with an emphasis on detecting failure initiation. Progression of damage is linked to spatial small temperature changes in composite single lap shear joints. The motivation of focusing the TSA-IR testing for initiation on the bondline can be explained through an FEA stress analysis of a typical lap joint (Fig. 1). The typical behavior in such a joint is the large concentration of shear and peeling stresses at either end of the lap shear joint. Note that the area of the highest stresses is closest to the bondline fillet.

The thermoelastic stress analysis theory is based on the first and second thermodynamic laws. The thermoelastic relationship for reversible and adiabatic thermodynamic events can be expressed as [28]:

$$\rho C_\varepsilon \frac{dT}{T} = \left[\frac{\partial C_{ijkl}}{\partial T} (\varepsilon_{kl} - \alpha_{kl} \Delta T) - C_{ijkl} \left(\alpha_{kl} + \Delta T \frac{\partial \alpha_{kl}}{\partial T} \right) \right] d\varepsilon_{ij} \quad (1)$$

where ρ is the material density, C_ε the specific heat for constant deformation, T is the temperature, C_{ijkl} is the elasticity tensor, α_{kl} the thermal expansion coefficient tensor, and ε_{kl} the strain tensor. In the TSA-IR method, during cyclic loading and the presence of reversible adiabatic conditions, an infrared detector measures an un-calibrated TSA-IR signal that is dependent on the material and surface properties. In this discussion we refer to the TSA-IR signal