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Health monitoring of scarfed CFRP joints under cyclic loading via electrical resistance measurements using carbon nanotube modified adhesive films

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ABSTRACT

This study deals with a structural health monitoring approach for adhesively bonded carbon fiber reinforced polymer joints. A modification of an epoxy based adhesive film with single wall carbon nanotubes allows for electrical resistance measurements through the joint. Cyclic fatigue tests of adhesively bonded scarf joints with simultaneous electrical resistance measurements are conducted to investigate the damage detection and localization of repaired composite parts during operation. The measured electrical resistance changes are compared to results from digital image correlation. Crack initiation and growth can be detected by an increase of electrical resistance. Furthermore, it is possible with parallel oriented ink-jet printed circuits to localize the damages occurred.

1. Introduction

The application of composites in structural aircraft parts has led to an increasing importance of composite repair techniques. Compared to riveting or bolting, adhesive joints offer important advantages as more uniform stress distribution, no disturbance of the aerodynamic contour, no damaging of the fibers, and lower weight penalty. The preferred method to repair composite aircraft structures is to use adhesively bonded scarf joints, which is the state-of-the-art repair technique for secondary structures in aircraft industry. However, for primary structures airworthiness bodies do not approve bonded repairs due to the absence of a non-destructive testing method for adhesively bonded joints [1]. Aircraft structures including repaired sections are subject to cyclic loading and fatigue-induced damages can lead to local degradation of the mechanical properties and may be crucial for the safety. Implementation of a structural health monitoring (SHM) system would give warning at an early stage of a damage and therefore allow corrective maintenance before failure of the repair occurs. SHM systems offer high potential for increased inspection intervals, reduced downtime and maintenance costs, and increased safety of the monitored structures. Several approaches to monitor composite structures during operation exist [2–7]. One promising SHM method for materials, which are not electrically insulating, is to conduct electrical resistance measurements [8,9]. For carbon fiber reinforced polymers (CFRP), several studies demonstrate that the high electrical conductivity of the carbon fibers can be used for in situ strain and damage monitoring via electrical resistance measurements [10–17]. However, polymers without conductive fibers are typically electrically insulating and therefore electrical resistance measurements are not possible. This applies for example for glass fiber reinforced polymers (GFRP) and most of the industrially available adhesive films. A modification of the polymer with carbon nanoparticles can lead to a conductive network resulting in an electrically conductive material with piezoresistive properties. A conductive network forms above a critical nanoparticle content, i.e. the percolation threshold, where the conductivity increases several orders of magnitude. Kupke et al. [16] and Muto et al. [18] first introduced the concept of exploiting the piezoresistive properties of carbon nanoparticle modified polymers for strain and damage monitoring by electrical resistance measurement. Compared to other nanoparticles, carbon nanotubes (CNT) offer the advantage that due to their high aspect ratio very low percolation thresholds can be obtained [19–21]. Several investigations proved the concept of carbon nanoparticle modification and resistance measurement for strain and damage sensing [22–31].

Health monitoring of adhesively bonded composite joints has been studied using different methods like for example lamb waves [32], digital image correlation (DIC) [33], and optical fibers [34]. However, only few studies on health monitoring of adhesively bonded joints via electrical resistance measurements exist.

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Mactabi et al. [35] showed that the electrical resistance change can be used to monitor the integrity of a CNT modified adhesively bonded aluminum joint. And Lim et al. [36] demonstrated CNT networks can be used to distinguish different types of damages in a hybrid composite/steel joint. In a recent study, we presented a method to detect and localize impact damages in adhesively bonded glass fiber reinforced structures [37].

This study aims to develop a non-destructive testing method to monitor the integrity of adhesively bonded scarf joints during cyclic loading. Conductive paths are ink-jet printed onto scarfed and electrically insulated CFRP surfaces and CNT modified adhesive films are manufactured to enable electrical resistance measurements through the bond line. Adhesively bonded scarfed CFRP joints are exposed to cyclic loading and electrical resistance measurements are carried out. Damage mapping is used to detect and localize damages and the results are compared with strain measurements using DIC.

2. Materials and specimen preparation

The used carbon fiber reinforced prepregs consist of an epoxy matrix and carbon fibers (HexPly M21/34%/UD194/T800S by Hexcel). CFRP plates with the laminate layup $[-45/90/45/0]_S$ were laminated from prepregs and cured in an autoclave process at a temperature of 180 °C and a pressure of 7 bar for 120 minutes in a nitrogen atmosphere. Subsequently, the plates were tapered with a scarf angle of 2.86° (corresponding to a thickness to length ratio of 1:20) using a diamond coated milling cutter (OptiMill-Composite-Speed M7218-1000AQ by Mapal) operated in a CNC mill. To achieve electrical insulation, a phenolic resin based coating (2242 by Kal-Gard) with a thickness of 6.9 ± 1.7 μm (measured by light microscopy) was spray applied onto the surface of the scarfed CFRP. Conductive paths out of silver nanoparticle based ink were inkjet-printed onto the scarfed and coated areas using a single nozzle print head (by microdrop Technologies) with a nozzle diameter of 70 μm. The conductive paths have an interspace of 8.75 mm and were placed parallel to the edges of the specimens. The ink consists of silver nanoparticles (31.0 wt%) with a D90 value of 60 nm dispersed in the solvent butyl carbitol (68.5 wt%) and ethylene carbonate (0.5 wt%). Details on the manufacturing process of the used ink are described elsewhere [38].

For the manufacturing of the adhesive films, epoxy resin (EPON LVEL 828 by Hexion Inc.) and 0.5 wt% of single wall carbon nanotubes (SWCNT) (Tuball by OCSiAl) were mixed and dispersed using a three-roll mill (120E by EXAKT Advanced Technologies GmbH) to obtain a masterbatch. The milling process was conducted seven times at constant rotational speed of the rolls of 33 min^{-1}, 100 min^{-1}, and 300 min^{-1}, respectively. To achieve a good dispersion quality of the SWCNT in the resin, the gap widths between the rolls were 120 μm and 40 μm for the first step, 40 μm and 13 μm for the second step, and 13 μm and 5 μm for the subsequent five steps. A minimum gap size of 5 μm results in a uniform dispersion and a retention of the aspect ratio of CNT as shown earlier by Gojny et al. [39]. Recently, we reported on a uniform dispersion of SWCNT in epoxy by using the same set of parameters [31]. From this dispersion, the company 3M Germany GmbH manufactured adhesive films with a SWCNT content of 0.1 wt%. The adhesive film was sandwiched between two scarfed surfaces and cured under vacuum in an autoclave process at a temperature of 125 °C and a pressure of 5 bar for 120 min in a nitrogen atmosphere. No additional sintering process was necessary, because the autoclave process involves a sintering of the conductive silver paths. To enable reliable contacting for resistance measurements, stranded copper wires were connected with the printed conductive paths using conductive silver paint (Acheson Silver DAG 1415 M).

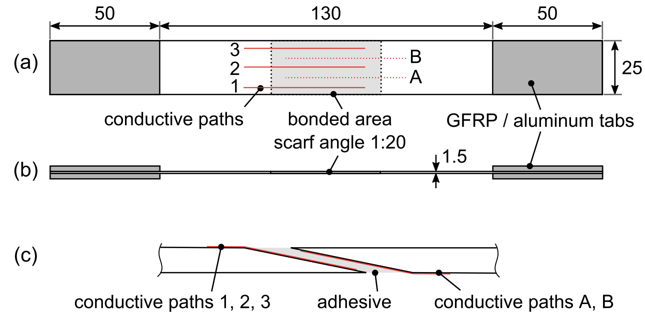

Fig. 1. Specimen geometry and conductive path design.

GFRP with fibers oriented in ±45° direction and aluminum tabs with a width of 50 mm and a thickness of 1 mm were bonded onto both ends of the cured plates with solvent free two-part epoxy adhesive (UHU plus endfest 300) at 80 °C for 30 min. Specimens with dimensions of 230 mm × 25 mm × 1.5 mm with a free specimen length of 130 mm were cut from the plates using a water-lubricated diamond coated saw blade. The edges of the specimens were polished up to 1000 grain size abrasive paper. Specimen geometry and the arrangement of the printed paths are shown in Fig. 1. Here, the specimen is shown schematically from the top (a) and from the edge (b): The conductive path design is shown in (a) and (c). Paths 1, 2, and 3 are placed on one scarfed area and the conductive paths A and B are located on the other scarfed area, i.e. on the opposite side of the adhesive.

3. Experimental

Axial, constant-amplitude, force-controlled, cyclic fatigue tests with coupon specimens were conducted using a servo-hydraulic 100 kN fatigue testing machine (Instron/Schenk). Specimens were clamped with a pressure of 140 bar using hydraulic clamps. Ambient conditions were kept constant with temperature and relative humidity of 23 °C and 50%, respectively. The specimens were loaded with a sinusoidal force in the tension-tension regime with a load ratio, R, of 0.1 and a testing frequency of 5 Hz. Testing procedures and data acquisition were carried out using the software WaveMatrix (Instron). For each test, maximum force (F_{max}) and minimum force (F_{min}) were kept constant (see Fig. 2). DC electrical resistance measurements during fatigue testing were conducted using a digital multimeter (Keithley 2000). Four resistance combinations, namely A to 1, A to 2, B to 2, and B to 3, were measured successively with a measurement duration of 1 s (five cycles) per

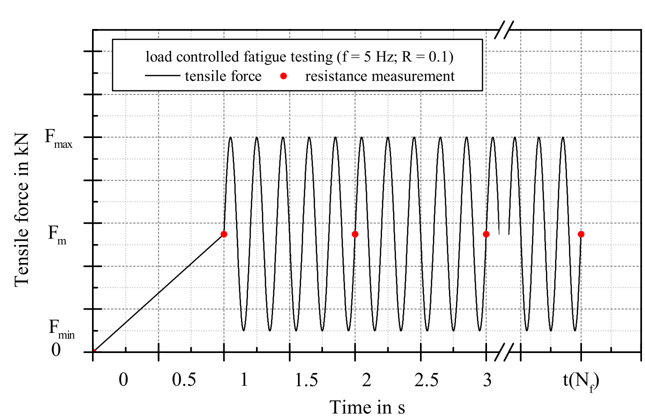

Fig. 2. Schematic test procedure for fatigue tests with electrical resistance measurements.