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Ultrasonic analysis and lock-in thermography for debonding evaluation of composite adhesive joints

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ABSTRACT

Glass-fiber reinforced thermosetting plastic adhesive joints were characterized through ultrasonic imaging and lock-in thermographic analysis for assessing the adhesion quality before being subjected to static tensile mechanical tests and to accelerated aging cycles.

The mapping of each sample has been obtained. Visual testing were performed on all specimens after the mechanical tests in order to obtain a comparison with ultrasonic and lock-in thermography technique.

A quantitative analysis has been carried out to evaluate the ability of lock-in thermography in investigating inadequate bonding and obtaining the validation of the technique by the consistency of the results with the well-established ultrasonic testing.

1. Introduction

Wind turbine blades are made from polymer composites to provide high specific stiffness, strength, and good fatigue performance. However, large composite structures are prone to manufacturing defects such as delamination and adhesive failure, which can lead to crack initiation and propagation [1].

Adhesive bonding failure is a key manufacturing defect typical of blade joined using adhesives paste of several millimeters thick. In fact, they can be expected to experience significant static and fatigue loads under various environmental conditions over their service life. National renewable energy laboratory, USA statistics shows in Fig. 1 that manufacturing defects and in-service damages are the main reason for early blade failure [2].

Despite great attention given to maintain quality in manufacturing processes, the data available for joints of this class with composite adherents indicate significant sensitivity to adhered properties and surface preparation, adhesive composition (chemistry, additives, mixing, and curing), adhesive thickness, temperature, and moisture, as well as joint geometry [3].

Many researchers have done extensive work to identify different types of defects in adhesive joints and have suggested suitable non-destructive test methods to evaluate them [4–8].

Although, the influence of overlapped reflections, scattering and attenuation of the reflected ultrasonic waves from the multi-layered structure appears and the scattering effect also has a negative impact to the propagating ultrasonic waves and requires to use lower frequencies [9], ultrasonic methods have been widely used in the non-destructive testing and inspection of adhesive joints showing a high sensitivity to the defects commonly found in wind rotor blade.

The propagation characteristics of ultrasonic waves are used to determine material properties throughout the volume of turbine blade and to detect and characterize the surface and subsurface flaws and also are suitable for quality control and for estimation of the adhesion level between composite layers. The ultrasonic C-scan imaging can be used for the area mapping of the component [10]. C-scan is 2D image representation using ultrasonic wave signal acquired point-by-point as A-scan signal from the structure. For automated inspection, C-scan system consists of motorized scanner to move ultrasonic probe over the structure. Manual A-scan provides qualitative information whereas C-scan provides quantitative information about damage extent, type of damage, etc [11].

Thermal techniques can be also used to investigate defects in adhesively bonded components [12,13]. Stimulated Thermography is able to detect defects in homogeneous materials thanks to different thermal behavior that they have if subjected to a thermal stimulation. This behavior is due to the different thermal–physical properties involved in the heat transmission phenomena such as the thermal conductivity, the heat capacity at constant pressure and the density of material [12,13].

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In literature many works regard the application of stimulated thermography for the NDE of FRP strengthening system bonded on concrete structures [14–16]. In these works it was shown the capability of thermography for the estimation of defects and the strong and weak points with respect to other NDT techniques were highlighted.

The ability of thermography to characterized defects in adhesively bonded composite joints was demonstrated in various works [17,18]. In particular, Genest et al., [19] used flash thermography and a novel signal processing to improve the debond visibility and reduces the influence of the repair edges. The new technique was demonstrated considering simulated and real debonding in CFRP bonded patches. Quantitative analysis shows results in good agreement with ultrasonic and destructive technique.

In the work of Schroeder et al., [20] Pulsed Thermography was used to evaluate large automotive assemblies, composite parts and bonded joints. All tests were carried out with Flash Thermography technique that requires short cycle time and then can be used for on-line tests for part validation.

Johnson [21] proposes a new approach based on TSA (Thermoelastic Stress Analysis) technique to characterized the damage initiation and progression in FRP single lap shear joints. This technique allows to obtain information about the damage extent of material and can be used for the monitoring of damage during the fatigue test.

In this paper we analyze, the results of an experimental investigation aimed at determining the capability and reliability of the lock-in thermography [12,13,22,23] as a non-destructive method of assessing the integrity of glass-fiber reinforced thermosetting plastic (GFRP) adhesive joints used for the construction of wind rotor blades.

Different tests were carried out on single lap adhesive joints designed according to ASTM D 3165 [24], using lock-in thermography and ultrasonic C-scan technique. It was carried out a quantitative analysis in order to evaluate the ability and the advantages of lock-in thermography with respect to the ultrasonic C-scan technique that is considered well-established in literature for the debonding detection of joints.

2. Materials and methods

2.1. Specimens

Single lap adhesive joints were prepared as per ASTM D 3165 [24] standard using glass-fiber reinforced thermosetting plastic (vinyl ester GFRP) as substrate and a two part epoxy adhesive: AME6000 INF (Ashland Composite Polymers) and ADH 90.91 (Altana Electrical Insulation). Adherends were characterized by multiple layers of quadriaxial 0°/+45°/90°/−45° fabric glass-fiber and were obtained from a laminate fabricated using the technique of infusion of the resin under vacuum (VARI). Surface preparation was carried out according to ASTM D 2093 [25] standard for surface preparation of plastics. The panels, properly cleaned and treated, were placed inside a tool for bonding where they were lined up by reference pins. After spreading a thin layer of adhesive, the assembly was closed and the pressure was applied. As regards the conditions of care, they are observed as indicated by the manufacturer of adhesive.

The planar and three-dimensional geometry of the joints are shown in Fig. 2.

The single-lap samples were cut from the panels according to scheme imposed by ASTM D 3165.

Since the legislation provided for the use of metals, while the present study is based on adherends in composite materials, changes have been made, in the thickness of the adherends, which are set to a value of 2.5 mm, while the thickness of the adhesive remains equal to 0.76 mm.

A total of 12 single lap joints were used for the experimental tests and they were denoted by the initials VA followed by a sequential cardinal number and the indication of the production lot.

2.2. Hygrothermal aging

The aging cycles for testing were determined on the basis of the monthly average of maximum temperature, minimum temperature, and moisture percentage of the last 30 years in Alpine and Apennines Italian region at about 1500 m above sea level. The

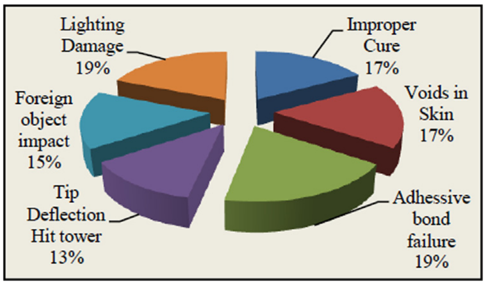

Fig. 1. Blade damages at manufacturing and operational stage [2].

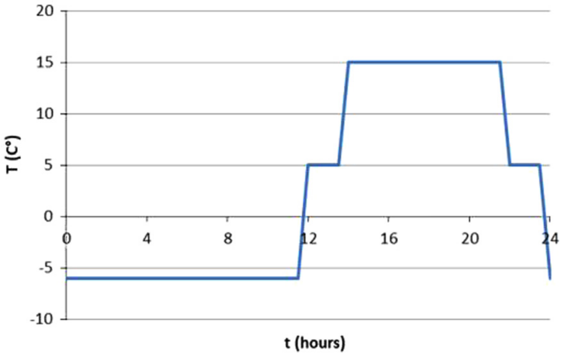

Fig. 3. Daily hygrothermal aging: cool, mild and warm sub-cycles within 24 hrs.

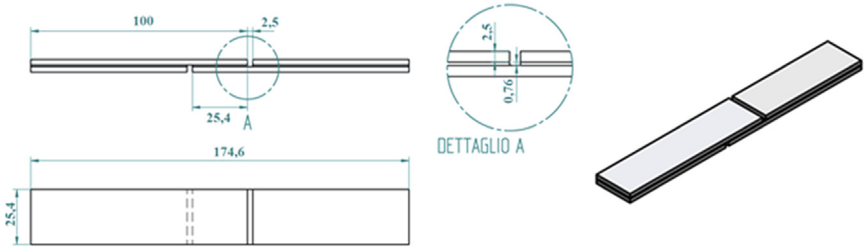

Fig. 2. Planar and three-dimensional geometry of the joints.