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Model of moisture absorption by adhesive joint

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ABSTRACT

Adhesive joints offer many advantages over traditional mechanical joining systems. Nonetheless, their use is limited since they can be adversely affected by extreme temperatures and humidity conditions. Moisture contamination (even 1–3% of the sample weight) in an adhesive can alter its tensile strength and compromise the structural integrity of the joint. Moisture absorption processes can be monitored using methods based on fibre Bragg grating sensors embedded in the adhesive material.

In the present paper, a finite element model of an adhesive joint between composite elements was analysed using the commercial code Abaqus™. The investigation contains two main parts: a thermal analysis and a hygro-mechanical analysis. The achieved results were verified using experimental investigation results for a sample with embedded fibre Bragg grating sensors that were applied to monitor the moisture-induced strains in the adhesive joint.

The achieved numerical results show good agreement with the experimental ones for all considered analyses. The presented models can also be used for the determination of moisture content in an adhesive layer especially in a range of 1.5–2.5% of the water content.

1. Introduction

Adhesive joints offer many advantages over traditional fastening methods, such as a more homogeneous stress distribution, aesthetic appeal, higher stiffness, high fatigue strength, low weight, the possibility to join dissimilar materials and corrosion prevention [1]. They are also preferable to traditional methods like mechanical fasteners that may require the drilling of the component. Drilling holes can be a source of damage for the material and they introduce undesired stress concentrations near the affected area [2]. Nonetheless, the use of adhesive joints is still limited since many of its properties are negatively affected by environmental conditions.

One of the most important causes for loss of mechanical strength in an adhesive joint and composite materials is moisture absorption [3–9]. By virtue of its polymeric nature, the ingress of water in an epoxy is associated with an increased separation between the molecular chains which causes expansional strains. This phenomenon is referred to as plasticization and it can alter the chemical structure of the component [10]. Moisture has important effects on composite performance because it causes degradation, especially in the polymeric matrix of composites [11]. Variations of moisture concentration results in changes in the dynamic characteristics of composite elements [12]. For the majority of composite structures, the increase of hygroscopic concentrations results in the decrease of mechanical properties of the material. For hygrothermal effect, it

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is noted that the variation of vibration frequency is caused by both the hygrothermal deformation and the change of material properties [13].

Moisture concentration up to 1% has fairly small effects on the dynamic characteristics of composite elements although it is noticeable [12]. Due to this, different models [14,12,15,13,16] have been developed to analyse the influence of moisture, temperature, fibre orientation and loading conditions on structure dynamic properties of composite laminates.

Moisture absorption by an adhesive leads to several changes in its physical and mechanical structure. It reduces the glass transition temperature T_g, tensile strength and lowers the ultimate elongation of the adhesive [8]. Thus, moisture absorption and moisture-induced strain monitoring is an area of high interest in the field of structural health monitoring (SHM).

The most important degradation processes due to moisture contamination (even 1–3% of water mass gain) in adhesive layers are: plasticisation [17–19] cracking [18], hygroscopic expansion of the adhesive [17,19] and deterioration of the adherend/adhesive interface [17–19]. The moisture distribution inside an epoxy component is necessary to fully assess the adhesive joint's mechanical response under known environmental conditions. The diffusion characteristics of moisture in an epoxy adhesive are critical factors to predict the moisture profile [8].

One of the experimental methods for determining the amount of moisture in an epoxy is based on FBG (fibre Bragg grating) sensors embedded into structural element during the manufacturing process [3,20,21]. FBG sensors written on silica fibre optics have many advantages: small size and weight, high corrosion resistance (both water and chemicals) and no calibration requirements [22]. The FBG sensor wavelength is linearly dependent on strain [23] and temperature [24]. Since the process of moisture absorption results in an increase of material volume reflected by internal strain changes, it can be measured by FBG sensors embedded into the analysed material layer [3,20,21]. Numerical simulations can be used to predict the mass gained by water intake and the mechanisms of diffusion through polymeric materials [25,26].

In the paper, several finite element models were created to simulate the thermal response, diffusion dynamics and strain development of the tested components and serve as a methodology for future studies in the area. The numerical analysis results were compared with experimental results performed on composite samples with adhesive layers with embedded FBG sensors. The experimental investigation was described in detail in a previous paper [20].

2. Adhesive joint - moisture contamination detection

The numerical analysis was performed on a sample composed by two elements of GFRP (Glass Fiber Reinforced Plastic) composites with a stacking sequence of (0/90/0/90/90/0/90/0) joined together by an adhesive layer with a thickness of 0.2 mm as it is presented in Fig. 1. The adhesive used was a two-part structural epoxy paste adhesive produced by Henkel Corporation and commercially known as Loctite EA 9394 Aero or Hysol EA 9394.

In the adhesive layer two FBG sensors were embedded parallel to main axis of the sample to measure volumetric change of the sample induced by moisture influence. The first one was located near the sample's center while the second one - more closely to the edge of the sample (see Fig. 1).

The soaking process was performed under stable temperature conditions (333.15 K ± 2 K). The sample was kept inside a box filled with water, up to 0.5 mm on top of the sample, for 2 weeks (336 h) (Fig. 1).

As it is visible in Fig. 2, the maximum amount of moisture that can be absorbed by a GFRP sample during 14 days of soaking is less than 1%. As the adhesive layer absorb more water than composite the numerical analysis was concerned on this part of the adhesive joint. However the water diffusion throughout composite elements was taken into consideration in mass diffusion analysis. The relative water gain *M(t)* was determined using the following relationship

$$M(t) = \frac{w_k(t) - w_{ref}}{w_{ref}} \tag{1}$$

where w_{ref} is the sample's weight when dry and $w_k(t)$ its weight at time t.

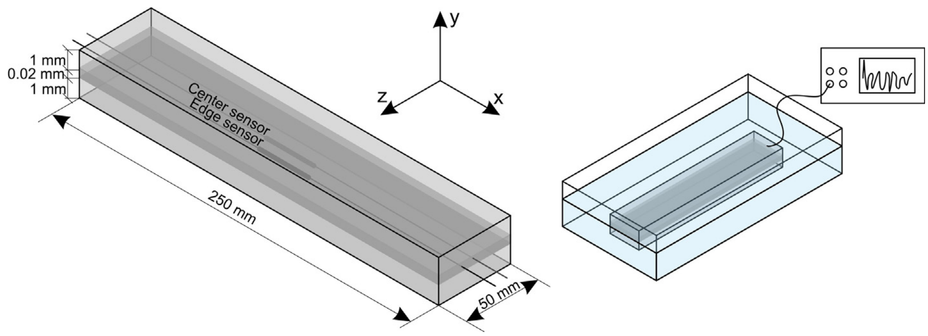

Fig. 1. Sample dimensions with two FBG sensors location in adhesive layer and measurement set-up.