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Numerical and experimental study of a SHM system for a drop-ply delaminated configuration

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ABSTRACT

The present paper presents the experimental and FE numerical analyses of a Structural Health Monitoring system for a drop-ply configuration. In order to verify the mechanical experimental setup of the assembling between the host structure and the piezo-film patches in term of constraint, transient and modal analyses are first performed in order to compare the experimental responses to those obtained by from the numerical analyses performed with the commercial code COMSOL Multiphysics®. Then the Finite Element modelling of the piezoelectric sensors, to be used in the numerical analysis of the assembled structure, is validated through the comparison with the experimental data provided by the sensors manufacturer. Lastly, dynamic experimental and numerical analyses are performed on the undamaged and damaged drop-ply configuration in order to verify the effectiveness of a damage index in highlighting the position of the delamination tips.

1. Introduction

Composite structures have had a wide development in the framework of aeronautics and aerospace industry particularly due to their mechanical properties that evidence better performance when compared to conventional materials. The modern technologies, indeed, allow to develop structural components characterized by different and also complicated shapes allowing weight saving while preserving high stiffness and strength values [1]. On the other hand, composite materials and structures are characterized by a very complex mechanical behaviour and this is particularly due to their inherent anisotropy and mismatch of materials among adjacent plies. Consequently high interlaminar stress arises resulting in damage phenomena that can drastically reduce the mechanical properties of composite structures. Among the damage phenomena arising in composite structures, the most common are fiber breakage, matrix cracking and delamination [2,3]. The last one can be addressed as one of the most severe failure mechanism of composites especially if it originates from fatigue loads and impacts or if it comes out as the de-bonding between the skin and the stiffeners in a drop-ply configuration [4]. In order to avoid catastrophic failure, deriving from undetected damage in composite components, periodic inspection and preventive maintenance of composite damaged structures represents a primary issue for the safe operation and management of this kind of structures [5,6].

In this framework the most spread and well established inspection techniques refer to Non-Destructive Evaluation methods (NDE) such as radiographs, acoustic, ultrasonic and [7], of course, visual inspection that, although represents the most widespread method to identify damage on aircraft in service [8], it does not allow to set the gravity of a defect. Moreover, the above listed NDE methods require the inoperability of the aircraft thus resulting in the increasing of the time and costs associated to the inspection and maintenance procedures [4,9]. Very promising alternatives to passive detection techniques are nowadays growing up due to the development of the so called smart structures and materials [10–12]. Among these, it is worth to refer to fiber optic sensors [13,14] that offers an alternative method for the monitoring of a structure and the consequent detection of a damage whilst the aircraft is in flight and thus avoiding time consuming associated to passive inspection techniques [15]. Experimental analyses on a fiber optic based SHM system for metallic components have shown the capability to detect the corrosion [16] with the possibility to be integrated within the material [17], while, in the framework of composite materials fiber-optic-based sensing system have revealed the possibility to monitor impact damage in large scale CFRP structures [13]. Real time Structural Health Monitoring system can also be obtained by means of piezoelectric materials that, in force of the direct and converse piezoelectric effects, can be used as sensors as well as actuators to obtain closed-loop smart structures whose components are able to sense, diagnose and actuate in order to perform their functions [18]. The main idea at the basis of a closed loop smart structures is to implement a SHM systems together with active repairs [19–22].

Focusing the attention on the Structural Health Monitoring systems based on the use of piezoelectric materials, different strategies have been developed to detect damage in structural components by means of

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sensors network. In the framework of Aerospace industry, where thin structural components are mainly used, the Structural Health Monitoring obtained by means of Lamb waves appears very suitable since it is possible to explore the whole thickness in a single interrogation [23]. Lamb waves were firstly used for damage detection in composite, such as delamination, presence of foreign material, and changes in fiber volume fraction of carbon/epoxy laminates, by Chimenti and Martin [24]. Further studies on Lamb waves for SHM have also focused on the detection of near-surface delamination as well as its size and depth by modifying the Lamb waves amplitude [25], on the characterization of the quality of bonds [26], or welds and joints [27], on the non-destructive characterization of composite components under both mechanical and thermal fatigue [28]. The interested reader can found a detailed review on damage classification using Lamb waves in composite structures in the work presented by Su et al. [29]. Although Lamb waves are very appealing for SHM, some drawbacks should be highlighted such as the propagation complexity of these waves (often associated with difficult analysis and interpretation), the requirements for baseline measurements and temperature-dependence and the needs for actuation (or excitation) of monitored structures that put lamb waves in the framework of active damage detection approach [30]. On the other hand, passive damage detection approaches do not involve any actuation. In this case, transducers are only used to sense local perturbations directly caused by damage, such as perturbation in the vibration parameters [31–36] or in the static and dynamic strain responses [4,37]. Passive damage detection can thus be used in conjunction with the active ones to increase the reliability of the SHM system in detecting damage in those regions of more interests. In the framework of SHM systems, based on the use of piezoelectric sensors from dynamic strain response, the authors have already developed a methodology able to identify and characterize crack in damaged isotropic structures [37] as well as delamination cracks originating at the skin/stiffener bonding interface of composite components [4]. The methodology has been investigated numerically by means of a Boundary Element code and the results have shown that a proper definition of a damage index, based on the electrical output of the piezoelectric sensors, can allow to identify the delamination tip position in drop-ply configuration [37,4] made up with isotropic or composite materials. However, no experimental campaign has been proposed to validate the methodology as well as the damage index effectiveness.

On the aforementioned basis, the present study presents the experimental validation of a SHM system for the detection of delamination in drop ply structures that could be extended to represent many aeronautical structural configurations. With the aim to check the effectiveness of the proposed SHM system for drop-ply configuration, isotropic PMMA material is used to arrange the monitored structure while piezo-film devices are used to arrange the sensor array.

The electro-mechanical dynamic response of the delaminated drop-ply configuration with the bonded patch is characterized under shaker test and the definition of the damage index, previously introduced by Alaimo et al. [37,4] to effectively identify edge delamination, is then experimentally validated.

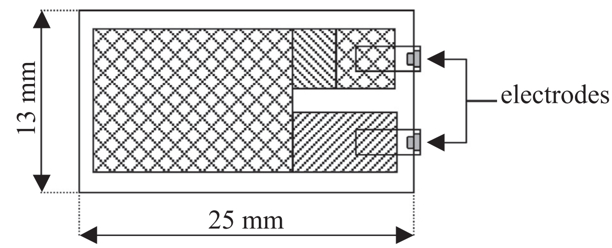

Fig. 2. Piezo film geometry characteristics.

2. Formulation of the problem

The analysed configuration is shown in Fig. 1 and it consists of an host structure made up by two different PMMA bars glued together, by means of epoxy resin SX10, to arrange a drop ply configuration. It represent a preliminary idealization of a drop-ply delaminated structure previously employed by Beuth [38] and Narayan and Beuth [39] to represent a bi-dimensional simplification of the adhesive joints between aircraft fuselage skins and stiffeners. The following configuration is here analysed to experimentally verify the sensing capability of the SHM system numerically analysed by Alaimo et al. [37,4].

The two PMMA bars are characterized by a rectangular cross-section with the height h = 10 mm and width w = 20 mm, while the different lengths of the bars are L_1 = 250 mm and L_2 = 270 mm respectively.

The sensor network is obtained by means of four piezoelectric film sensors Pro-Wave Model FS-2513P, bonded by means of cyanoacrylate to the upper surface of the drop-ply configuration. The arrangement of the piezoelectric network is shown in Fig. 1 being L_P = 45 mm the distance between two different sensors and L_C = 12.5mm the distance of the left hand side of the sensor from the left end of the host structure. The geometry of the piezo-film sensor is instead shown in Fig. 2.

Three different configurations have been investigated in order to test the proposed Structural Health Monitoring system and the effectiveness of the damage index: i) the Undamaged configuration without delamination referred to as "SU" (Specimen Undamaged); ii) Damaged configuration with a short delamination characterized by a delamination length $a = L_1/3$ named "SSD" (Specimen Short Delamination); iii) Damaged configuration with a Long delamination characterized by a delamination length $a = 2L_1/3$ named "SLD" (Specimen Long Delamination). In order to obtain the delamination between the two different PMMA bars a mylar film has been used to avoid gluing at the delamination interface.

The specimens are clamped at the left hand side and a force F is applied at the free end of BAR 2 in the thickness direction, see Fig. 1.

3. Sensor network layout and damage index

3.1. Piezoelectric sensor behaviour and modelling

The sensor network is obtained through piezoelectric patches bonded on the BAR 1 top surface, as schematically represented in Fig. 1 by the grey bold segments. The sensors chosen for the tests are polymer film of polyvinylidene fluoride (PVF2) which exhibits a conspicuous

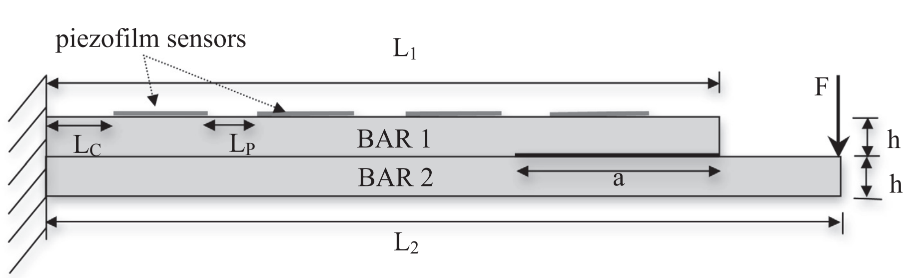

Fig. 1. Layout and geometry of the specimen.