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The nondestructive evaluation of the GFRP composite plate with an elliptical hole under fatigue loading conditions

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ABSTRACT

The accurate assessment of the fatigue strength for structures made of composite materials is difficult because of the great number of possible failure forms. The Structural Health Monitoring (SHM) systems are developed and applied in engineering structures for permanent monitoring the state of the constructions. In this paper the Lamb wave propagation method and the infrared thermography were applied to observe the fatigue damage evolution in the multilayered composite plate with an elliptical hole in the middle. The active pitch-catch measurement technique was introduced based on the surface mounted piezoelectric transducers. The localization of the piezoelectric actuator and sensors responsible for excitation and detection of the elastic wave was chosen based on the progressive failure analysis applied in finite element method. The multipoint measuring system was responsible for analysis of the elastic wave propagation phenomenon during the fatigue tests. The sequential measurement of the elastic wave parameters allow one to observe the state of the structure. The different parameters describing the wave propagation phenomenon like amplitude and time of flight was considered. The infrared thermography make possible of detection of the damage initiation and permanent monitoring of the structure. The measurement of the temperature distribution is straightforward and doesn't need complicated algorithms and software. Application of the coupled approach to the damage detection (piezoelectric transducers in SHM system with the permanent surface temperature monitoring) allow one to build cost effective system for detection of the damage initiation and for monitoring failure form evolution.

1. Introduction

The failure analysis of composite structures is the subject of interest to many researchers for decades. The great number of possible failure forms causes that the failure prediction of composite materials, especially laminates, is very difficult [1]. Nowadays, many efforts are dedicated to the development of failure criteria with the use of finite element method verified by experimental results [2,3]. The difficulties with the prediction of the final failure form result in the dynamic development of the Structural Health Monitoring (SHM) systems [4]. Generally, the damage detection systems were classified into several levels of analysis. The systems of the first level allow one only to confirm of the damage occurrence. The main task of the second level systems is to determine the localization and orientation of the defect. The assessment of the damage size is the aim of the third level systems. The mentioned levels creates the diagnosis part of the damage detection systems. The

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data from the diagnosis part can be applied to determine the remaining life of the structures (the forth level) in prognosis part of the SHM [5,6].

One of the most efficient method characterized also by relatively low cost of the monitoring system components is the elastic wave propagation method [7,8]. In most cases the monitoring systems use pre-installed piezoelectric transducers (PZT) to observe the changes in dynamic response of the analyzed structure. The assumption of the SHM analysis is the comparison of the intact and potentially defected structures. Thus, the signal features extracted from the response signal are considered and analyzed by damage detection algorithms. Different statistical measures were used by researchers to describe and quantify the damage [9]. It is worth to point out that the majority of the present SHM systems based on the wave propagation phenomenon deals with the plate-like structures. The elastic wave propagation method can also be applied to the structures under different cycling loading conditions [10]. From the durability point of view the permanent monitoring of the state of the structure during the normal service life is crucial especially in the cases of possible stress concentrations in the construction. The problem of fatigue failure starting from the hole edge is well known and commonly observed in engineering structure [11,12]. The analysis of the elastic wave propagation in composite structure with a hole is complicated because of the reflections from the boundaries and the interference phenomenon. Some methods are focused on the identification of the elastic wave scattering by a crack near the hole [13,14]. The damage index defined as an area between two response signals (from the intact and defected structure) was introduced and effectively used in the crack identification [15]. In laminated structures where the initiation of the failure form is associated with the delaminations or matrix cracking the wave attenuation and phase shift were effectively used in the damage characterization procedures [16,17]. The interaction between the elastic wave and the delamination in multilayered composite plates was investigated both numerically and experimentally [18,19]. Moreover, the prognosis of the fatigue life with the use of wave propagation method is also possible and was verified in the experimental tests [20,21]. However, many of the recent studies were based on the analysis of the single failure mode (delamination, crack, flaw, matrix damage). Most of the proposed damage detection procedures did not take into account the evolution of the defects understood not only as a development and growth of the single failure mode but also as the change and coupling between different damage types. The structures subjected to the cycling loading conditions are characterized by progressive degradation of the load carrying capacity. It is associated with gradual degradation of the material properties or/and progressive evolution of the fatigue damage. Thus, the damage detection system working during the normal service life of the construction should be able to detect different forms of the structural damage. In spite of the effectiveness and efficiency of the wave propagation based methods one can notice some limitations associated with the measurement techniques. For example analysis of the wave propagation near the holes is complicated because of the reflections from the boundaries [22,23]. The infrared thermography (IRT) is a non-destructive (NDT) method which was successfully applied to detection even relatively small defects in isotropic structures and multilayered composites. There are numerous works where thermographic methods were applied to observe the fatigue behavior of isotropic: steel specimens [24,25], aluminium alloys [26,27] or cast irons [28,29]. The application of IRT was also successfully used to determine the fatigue strength of composite laminates under tensile and compressive loadings [30,31]. Examples of the qualitative and quantitative results of the fatigue behavior of glass fiber reinforced polymers (GFRPs) [32,33], woven [34,35] and braided [36] carbon fiber reinforced polymeric composites can be found in the literature. To improve of the damage detection capability, the hybrid testing systems are presently being developed for monitoring and quantifying the fatigue behavior of materials. For example, combinations of standard techniques such as acoustic emission (AE), Digital Image Correlation (DIC) and Infrared Thermography (IRT) [37], Lock-in thermography and AE [38], passive IRT and AE [39] were tested by researchers. The hybrid approach to the damage detection and monitoring, focuses all efforts not on the methodology but on the use of all advantages of the applied methods to improve effectiveness of the system.

It is wort to point out that most of this works were focused on passive measurement techniques. Thus, the purpose of this paper is the experimental validation of the hybrid system based on the active wave propagation method and infrared thermography. Prediction of the failure forms coupling in the laminate based on the unidirectional fiber reinforcement is complicated. The failure form initiation depends on the curvature of the hole in the area of stress concentration. The classic form of the fatigue crack evolution was observed in the composite woven structures with circular and elliptical hole [40]. The problem of damage evolution in multilayered structures made of unidirectional plies with different than circular stress concentrators with permanent monitoring of the defects was not considered earlier. In this paper the elastic wave propagation method based on the multipoint PZT transducers system and the infrared thermography were applied during the fatigue tests of the multilayered composite plates with an elliptical hole. The fatigue tension tests were prepared based on ASTM standards D7615 [41] and D5766 [42], however, the aim of the tests was to observe the damage evolution of a composite plate, thus some modifications were introduced (e.g. geometry, designed grips). The number and localization of the actuator/sensors was chosen after finite element analysis of the failure form. The progressive damage analysis [43] applied in Ansys FEM package was used to observe the failure form evolution separately for matrix and fibers. The experimental fatigue tests of the composite plate with an elliptical hole were carried out under tension cycling loading conditions. Two plates were considered. Each of the cases was analyzed with the different amplitude of the load to verify the intensity of the load carrying capacity degradation.