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Fatigue damage growth monitoring for composite structures with holes

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ABSTRACT

The problem discussed in the present paper deals with theoretical (numerical) and experimental analysis of static and fatigue problems for composite open holes laminated panels. The novelty of our approach depends on the application of the hybrid experimental methods and the comparison of their effectiveness in the description of complicated fatigue problems arising in the analysis of the behavior of laminated panels with open holes and subjected to tensile loading. Three experimental methods are used herein: the infrared thermography (passive), the structural health monitoring (active) and the digital image correlation. The experimental investigations are supplemented by the finite element description of the problem dealing mainly with the static behavior, monitoring the development and final fracture of composites. The considerations concern the laminated panels oriented at ± 45° with different types of holes, i.e. vertical elliptical, horizontal elliptical and circular.

1. Introduction

Fatigue problems in the area of polymer matrix composites have little in common with metal fatigue. However, methodologies for life predictions and evaluation of the S-N curves (stress vs number of cycles) used in metals were carried over to fatigue testing of composite materials. Similarly, as for metals fatigue studies are conducted under the conditions of a constant frequency and constant amplitude profile (defined by the parameter $R = \text{load}_{min}/\text{load}_{max}$). Dealing with cyclic loading, the assessment of composite multilayered structures fatigue behavior remains an open problem in the literature.

Theoretical modeling of progressive damage accumulation and failure in composite materials/structures subjected to cyclic loading is associated with solving a highly nonlinear problem that includes large time steps required to resolve load cycle in a structure's load trajectory. The common idea of computational approaches is to approximate the evolution of a structural failure using the response from a small number of resolved cycles within the load trajectory of the structure and to interpolate the response evolution between the resolved cycles.

As the first for use by computers the rainflow algorithm has been adopted since the 1960s – Matsuishi and Endo [1]. The application of that method to the analysis of composite structures is presented, e.g. by Muc [2]. Chaboche [3], Chow and Wei [4] proposed the use of the cycle jump method, Acharya and Savant [5] the manifold-based multi-temporal modeling, Joseph et al. [6], Chakraborty and Ghosh [7] the wavelet transformation. In numerical investigations, a key challenge is the simultaneous treatment of multiple time for evaluation of the long-time degradation and failure response of composite structures and finally, the confrontation of the results with experiments.

Non-Destructive Testing (NDT) methods seem to be necessary to provide structural designers an effective tool to incrementally control and document damage growth as a function of fatigue cycles before failure. It allows us to develop and validate progressive damage analysis. Sims [8] discussed in details the fatigue test methods as well as fatigue data and test requirements. The author also focused attention on the problems of standardization and normalization of fatigue experiments and simultaneously he emphasized the necessity of continuous monitoring of degradation during fatigue testing. In the last decades for continuous monitoring of defects in polymer matrix laminated structures, a lot of experimental methods have been developed and they are known under the common term of Non-Destructive Testing methods. Kuhn et al. [9] proposed to divide the existing NDT methods into five groups relating to the physical methods of investigations: a) mechanical (ultrasonic or acoustic emission), b) thermal (thermography), c) magnetic (Eddy current), d) X-ray (tomography) and e) visual (penetrant testing or CCD camera). The authors introduced six criteria characterizing the suitability of the particular NDT techniques in the examination/evaluation of an individual problem.

The purpose of this paper is to discuss and compare the experimental observations used for the detection of defects arising during fatigue tests of composite structures with holes subjected to tension. From the existing techniques three are investigated more carefully, i.e. visual (Digital Image Correlation – DIC), ultrasonic (Structural Health Monitoring – SHM) and thermal (passive thermography) – Fig. 1. The

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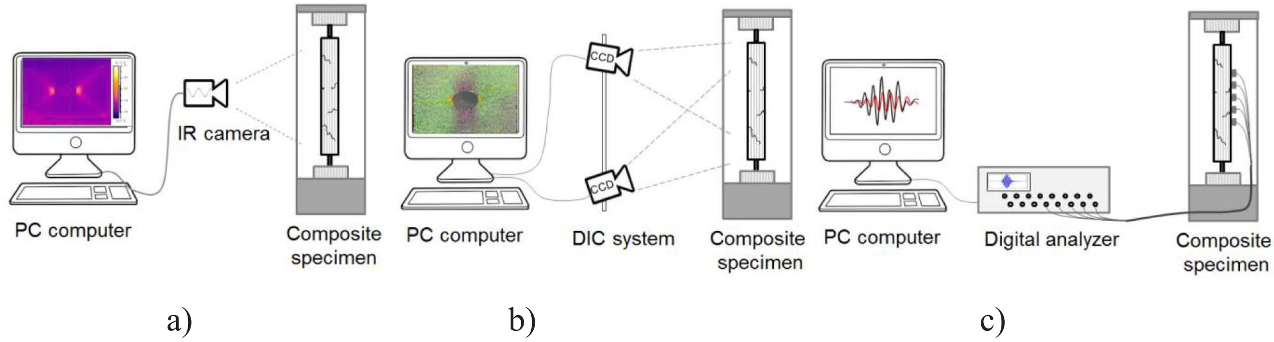

Fig. 1. Schematic set-up of experimental NDT techniques: a) thermal (passive thermography), b) visual (DIC), c) ultrasonic (SHM).

aim of this study is to emphasize the advantages and weaknesses of the methods mentioned above.

Giurgiutiu [10] introduced the classification of SHM methods dividing them into passive and active sensing. In the first group piezoelectric (PZT) sensors collect and monitor the structural signals over the time. In the second case, actuator transmits signals and sensors pick up structural responses. The waves can be elastic or electromagnetic. The Lamb wave-based fatigue crack size quantification and remaining useful fatigue life and residual stress/strain predictions were considered in Refs [11–16]. Sherafat et al. [17] analyzed the Lamb wave distributions to evaluate the integrity of composite skin-stringer joints. SHM of bonded repair patches subjected to cyclic loadings was discussed by Baker et al. [18].

Chiachio et al. [19] formulated a fatigue damage propagation model based on available SHM data. They discussed various aspects of a design of a prognostics health management (PHM) system. The similar problems dealing with the remaining useful life (RUL) of composite structures were considered by Loutas et al. [20]. More information on formulations and analysis of composite structures with the use of SHM methods can also be found in Refs [21–23].

When a composite material or a composite structure is subjected to cyclic loading, its temperature varies. Therefore, infrared thermography (IRT) offers an ideal, cost-effective NDE (Non-Destructive Evaluation) solution for a wide range of in-service and manufacturing industrial applications as it is presented in monographs [24–27]. The infrared thermography technique can be applied in a passive or active mode: the first is usually applied on materials/structures, which experience a different temperature than the surrounding materials; the latter needs an external stimulus to induce a surface temperature variation. Passive thermography is somewhat qualitative, whereas active thermography allows both qualitative and quantitative analyses to be performed [26]. A review of the scientific results in the literature, related to the application of the thermographic techniques to composite materials has been presented by Vergani et al. [28]. IRT was used to detect damage growth in various types of composite structures subjected to cyclic loads, e.g. three stringer panels Zalameda et al. [29], cylinders Zalameda et al. [30], cylindrical shells with forced delaminations Pastuszak and Muc [31], woven roving plates Rodrigues et al. [32], woven roving plates with holes Toubal et al. [33], unidirectional CFRP plates with holes Nixon-Pearson et al. [34]. In the area of fatigue testing, Thermoelastic Stress Analysis (TSA) [35–37] enables a full field visualization of surface stress distribution – the active IRT. The evaluation of fatigue strength/durability/limit is also possible by several passive thermography methods such as Risitano method [38,39] or Meneghetti method based on energy dissipation [40].

The Digital Image Correlation (DIC) method allows us to obtain accurate displacement and surface strain distributions of the analyzed isotropic or composite structures under static or cyclic loads. For 2D measurements, only one camera is enough, but to evaluate 3D displacement fields, two or more cameras are required in image acquisition. The broader discussion of this method as well as the existing variants of numerical packages suitable for the analysis is presented by Sutton et al. [41]. The possibility of applications depends entirely on a particular problem considered by researchers. Crupi et al. [42] analyzed rectangular specimens made of short glass fiber/polyamide matrix and used DIC to identify the fracture location in the tensile tests. Xu et al. [43] implemented the DIC analysis to correlate the deformations between grips and the center of textile composite specimens subjected to tensile cyclic loads. Makeev [44] applied the DIC technique to determine interlaminar shear stress distributions and their variations with the number of cycles for carbon/epoxy composites. Zhao et al. [45] evaluated the fatigue life and the damage evolution for composite bolted joints, whereas Van Der Sypt et al. [46] measured 3D deformations on the pin surface for low cycle fatigue loads. Sun et al. [47] created the complicated 3D high speed and 2D DIC system suitable for the analysis of specimens with wrinkles under impact loading.

2. Experimental set-up

2.1. Materials and specimens

The material used in the fatigue tension experiments was a unidirectional glass/epoxy composite and a glass woven roving fabric/epoxy resin. Their mechanical properties are given in Table 1.

All unidirectional specimens were manufactured using the autoclave technique under the pressure 0.4 MPa and cured at the temperature 135 °C. The samples made of plain woven roving fabric were produced with the aid of the vacuum bag molding method and cured at the temperature 120 °C. All specimens were stacked in eight layers and after curing their total thickness was equal to 2.2 mm. The dimensions of the specimens are illustrated in Fig. 2. It is assumed that the positions of the screws determine the total length of specimens at the *y*-direction. The holes in the panels were cut off using the numerically controlled machine. The diameter of the circular holes was equal to 50 mm, whereas the semi-axes of the ellipses are following: vertical ellipse $a = 17.5$ mm, $b = 35.7$ mm; horizontal ellipse $a = 17.5$ mm, $b = 35.7$ mm.

Table 1
Mechanical properties and fiber directions of the tested specimens – "0°" means the warp direction.

Materials	Fiber direction	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}
Unidirectional glass/epoxy	± 45°	46.4	14.9	5.2	0.27
Woven roving fabric glass/epoxy	0°	62	62	7.8	0.26