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# Fatigue damage evaluation of carbon fiber composite using aluminum foil based strain sensors

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ABSTRACT

For the development of a technique for cyclic deformation assessment with the use of aluminum foil sensors (with thickness of 80 μm) glued onto the specimen surface the fatigue tests of carbon fiber reinforced composites were carried out. The DSLR camera mounted onto an optical microscope was used for capturing the images of sensors to reflect strain induced relief, which than was numerically estimated using various informative parameters (Shannon entropy, mean square error, fractal dimension and Fourier-spectrum energy) in order to obtain the cyclic deformation assessment of composite. The results are discussed in view of application of this method for the development of structural health monitoring (SHM) approach.



## 1. Introduction

Composite materials, reinforced with carbon fibers, with their superior properties are widely used in the industry, especially in aerospace. The most common structural composites are laminates with unidirectional or woven fiber layers and a thermosetting matrix. The amount of reinforcing fibers can be easily varied, so the designer can create materials with properties best suited to the specific loading conditions. This approach, combined with low density of fibers and their high strength, provides lighter and more durable composite structures in comparison with conventional heterogeneous materials. In addition, composites are corrosion resistant and have good manufacturability.

Unlike metals composites have complex heterogeneous structures with various reinforcement directions, different properties of binder and filler. Due to the complexity of structure, with many fiber/matrix interfaces, there are a lot of defect types that might nucleate during operation (matrix cracking, fiber breakage, delamination, fiber pull-out, etc.). In this regard it is relevant to develop new techniques for strain evaluation under different loading schemes and conditions [1–3]. Besides development of the method itself it is of importance to find out numerical parameters to be extracted during surface images processing to correctly characterize deformation and fracture processes occurring in a loaded material [4].

However, during the in-service life the structures are loaded mainly cyclically with applied stresses below yield strength that can give rise to fatigue failure. Thus, for metals, fatigue damage is related to the formation of crack at stress concentration areas, which produces main crack with further loading. DIC method allows one to detect cracks on the surface of the specimen and monitor their opening and propagation velocity. The fatigue failure of composite materials is an extremely complicated process because of a lot of heterogeneities and non-uniformities: complex multilayer heterogeneous structure

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to vary mechanical response in each ply; sudden brittle failure that can occur at a variety of structural levels due to the accumulation of integral material damage (cracks, chips, delamination and fiber breakage). All these gradually reduce the stability of mechanical properties of composites and require comprehensive study with experiments as well as gaining numerical estimation under loading [5–7].

Many recent papers on the subject of non-destructive testing are devoted to structural health monitoring (SHM) systems. Such systems can provide information as the damage occurs and significantly improve the safety of operation, as well as expand the time intervals between the scheduled full-scale diagnostics events.

In the literature an approach described to the monitoring of materials under fatigue is related to the application of thin single crystal foils referred to as "smart sensors" [8,9]. This method is based on optical registration of images of foil (sensor) glued onto the specimen surface. Due to the cyclic loading the strain relief on the foil is formed and it is captured by digital camera. Digital processing of images allows one to calculate the informative parameters to assess the damage state of the material. In [8] "smart sensors" made of single crystal aluminum films were used to evaluate the mechanical state of AA2024 specimen during cyclic tension tests. In [10] the possibility of thin metallic foil sensors application in aeronautics is discussed. There are three fundamentally different functions of such sensors: load path detection, fatigue life sensing and crack assessing. Support to comply with the Airbus directives and airworthiness rules was given. Expectations in terms of performance and user interface were suggested in the paper.

However, in the above-mentioned papers "smart sensors" are offered to apply at fatigue damage evaluation of metals. The aim of the present study is to evaluate the possibility of application of such sensors for composite fatigue evaluation, as well as to develop a set of informative parameters for image processing. Early in [11,12], we developed a technique to study the deformation of composites under static loading based on the data of digital image correlation and acoustic emission.

## 2. Material and methods

Carbon fiber reinforced composite (CFRC) is pseudo-isotropic composite made of unidirectional carbon fiber layers with lay-up $[0°, 45°, -45°, 90°]_{2S}$ with epoxy matrix. Fig. 1 presents the drawing of the specimen with two edge notches and glued Al foil sensor. The thickness of the specimen is 3.3 mm. The specimens were cut with the use of diamond cutter Struers Secotom-10. Aluminum foil was glued by cyanoacrylic glue and then polished.

Fig. 2 presents two images of specimen before testing and after failure of the specimen. It is seen that foil on the untested specimen is polished, while the foil surface on the fractured specimen due to the strain relief becomes diffusely reflecting (matte).

Cyclic loading were carried out with the use of servo-hydraulic testing machine UTM Biss-00-201. The loading scheme is cyclic tension with cycle asymmetry of $R = 0.1$. The images of sensor (Fig. 1, image size 5184 × 3456 pixels, spatial size 12 mm × 8 mm) were captured by DSLR camera Canon EOS 550D mounted onto optical microscope. The image capturing device was located normally to the specimen surface. The specimen is illuminated with two light sources (Fig. 3) and imaged with DSLR camera connected to a PC, which controls cyclic loading. Then the images are processed for calculating informative parameters evaluating the changes of strain relief.

There were two light sources used: halogen photo lamp and point LED. Halogen lamp is located at *xz* plane at an angle of 45° to the *x* axis for source of background illumination. Point LED is oriented at the angle of 10° to the *x* axis to contrast strain

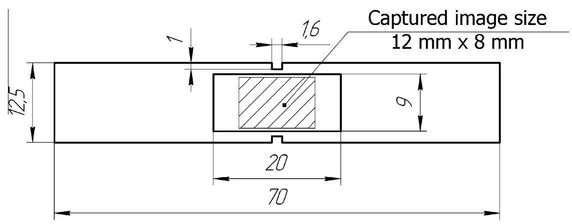


**Fig. 1.** Drawing of the specimen with glued sensor.

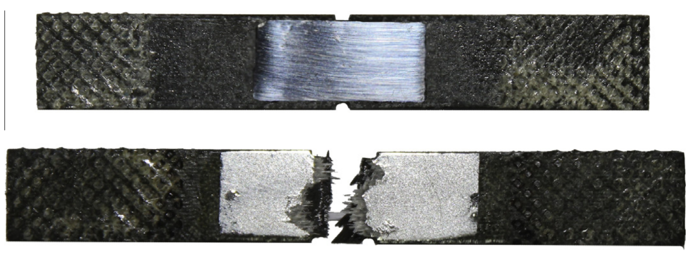

**Fig. 2.** Images of untested and fractured specimens.

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