EVALUATION OF IMPACT DAMAGE EFFECT ON FATIGUE LIFE OF CARBON FIBRE COMPOSITES

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Carbon fibre in polyphenylene sulfide composites became popular material in aircraft industry but its fragility and low resistance against impact loading limits the application of these composites in aircraft primary structures. The article deals with experimental investigation of the mechanical response of damaged composite. Material degradation of intact and damaged specimens during fatigue tests was investigated. The changes in natural frequencies, ultrasound wave propagation and bending stiffness were chosen as damage parameters. The entire fatigue life of intact and damaged specimens was studied in the article by all the presented methods. The accuracy and reliability of assessment of damage parameters were compared. Comparison of accuracy and reliability of presented method for assessment of damage parameters is also given.

Keywords: impact damage, carbon fibre composites, material degradation

1. Introduction

The material research in the field of aircraft construction has been focused on strong lightweight materials from the beginning of aviation. For several decades light alloys mainly based on aluminum compounds dominated in aircrafts' construction due to unaffordable prices of composite materials. However, in these days composites play a significant role in the aerospace industry. The legacy constructional materials are being replaced by mainly composites with carbon fibers. Composite materials are preferred to metals because of their strength to density and stiffness to density ratios given by synergic effect of their micro-structure. Although behaviuor of the applied materials is sufficiently known to be operated safely in civil aircraft, a complete understanding of these materials behaviour is yet to be gained.

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Reliable and non-destructive testing of composite materials is intensively investigated topic. Standard methods used for investigation of structural damages (such as notches and cracks) in conventional materials can not be applied on composite materials. These materials have to be investigated by other methods such as in this paper used modified impulse excitation technique (IET) and ultrasoud. Used for these methods were non-destructive testing of carbon fibre composite with polymeric matrix and compared with results of standard three-point bending test. Composite material of this type is mainly used in aviation industry and is planned to be vastly used as a main construction material of fuselage, airframe and wings. Therefore, it is very important to evolve reliable methodics of non-destructive testing of this material. One of possible approaches enabling to decide whether the structure was significantly damaged is desribed in this article.

2. Materials and methods

A special class of fibre reinforced material - carbon fibre in polyphenylene sulfide (C/PPS) composites became popular material in aircraft industry but its fragility to impact loading limits the application of C/PPS composites in aircraft primary structures. The knowledge of the process of damage accumulation and identification of parameters connected to material degradation plays an important role in the safe operation of structures and equipment. Changes of mechanical properties, namely of bending stiffness coupled with microstructural changes and acoustic properties were investigated to obtain complex information about whole fatigue life of the composite.

2.1. C/PPS composites

C/PPS composite is an advanced material used mainly in aerospace industry or other hi-tech applications. The material consists of quasi-isotropic 8-ply of carbon fabric bonded by thermoplastic matrix. The matrix is the main difference from more common composites based on epoxy resin, i.e. thermosets.

Modulus of elasticity of carbon fibers reinforcement prepared from high-stiffness poly-acrylonitrile is in range from 40 to 400 GPa [1]. The differences are given by various manufacturing methods. Other mechanical properties of C/PPS composite are in detail described in manufacturer's datasheet [2]. The set of specimens with rectangular shape with dimensions of 250×25 mm were cutted from plate with thickness of 2.5 mm.

2.2. Impact damage

The experimental procedure was a carried out on set of samples with four different levels of initial impact damage: i) intact samples ii) impacted by impactor with diameter 10 mm and energy 10 J iii) impacted by impactor with diameter

20 mm and energy 10 J iv) impacted by impactor with diameter 20 mm and energy 20 J.

FIGURE 1. Impact damage performing using drop tester

2.3. Fatigue loading

Before fatigue testing the dispensation tensile strength was measured by standard test. Average measured tensile strength reached 31 kN, independent on initial impact. Sinusoidal run with mean level 8 kN, amplitude 7 kN and frequency 4 Hz was chosen. Higher frequency would have caused heating of the sample with influence on the response of the material to the loading.

Servo-hydraulic Instron 1603 loading machine was used for the fatigue testing. The control frequency 1000 Hz and displacement transducers were chosen to guarantee precise run of the experiment [3]. Fatigue experiment was several times interrupted at predefined intervals and number of cycles. The damage indicators were investigated after 0, 1000, 5000 and 10000 cycles.

2.4. Ultrasonic measurement

Experiment was carried out using testing device USG 20 used with a 250 kHz transducer (USG-T) and receiver (USE-T). From physical nature of the ultrasound, the wave propagate mainly through environment with the greatest density, therefore the velocity only in the fibres was measured [4]. The velocity change was not significant therefore it can be assumed that the fibers are strenuous in the elastic region and the degradation occurs mainly in the matrix and by pulling fibers from the matrix.

2.5. Acoustic measurement

IET method is an experimental technique that is able to evaluate Young's modulus and shear modulus using natural frequency and power spectral densities (PSD) [5]. Change in elasticity properties indicated by natural frequency shift can be used to investigate fatigue degradation of material [6]. However, natural

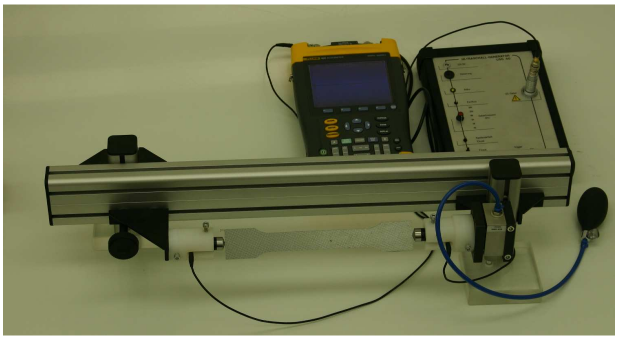

Figure 2. Ultrasonic measuring device with pneumatic fastening of the specimen

frequency identification by IET has remarkable limitations. The most significant limitation in case of our application was represented by unsatisfactory results in natural frequency determination for relatively small and flat specimens [7]. Hence, measurements described in this paper were performed using modified IET method that has the following properties: i) specimen was fastened vertically and in two points only, with one degree of freedom ii) contact of constraints with specimen‘s surface and its reaction force was minimized iii) sound of natural frequency was caused by impact of small steel pellet (diameter 2.5 mm) iv) impacts may be performed repeatedly at the same conditions and at the same point on specimen's surface. Custom-build experimental device was designed according to these requirements. PSD of natural frequencies for intact and fatigued (50000 loading cycles) specimen are depicted in Fig. 3. Decrease of natural frequency and PSD are clearly visible.

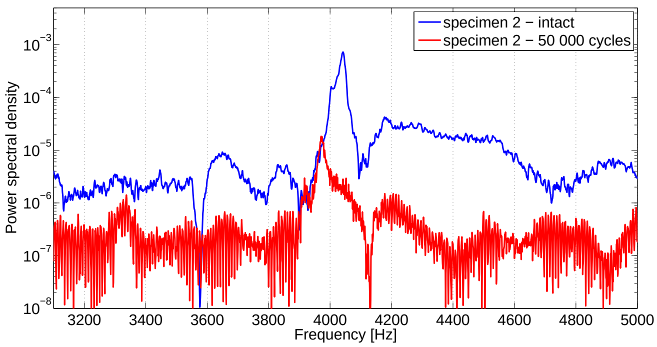

Figure 3. Measured decrease of natural frequency

2.5.1. *Experimental device.* Custom-designed experimental device is shown in Fig. 4 and consists of: i) wooden base plate – the base connects all parts of the device into one compact set ii) fasteners frame – made of prefabricated normal precision steel profiles. Specimen fastening is provided by means of two coaxial needles. Needles work as a clamp with minimal contact surface iii) working part – this part consists of mechanism with ability to be set in 5 different geometrical positions and alluminium tube providing rigid lead of steel pellet to specimen's surface. Mechanism can be fixated in any adjusted position. This property ensures stable conditions during multiple testing.

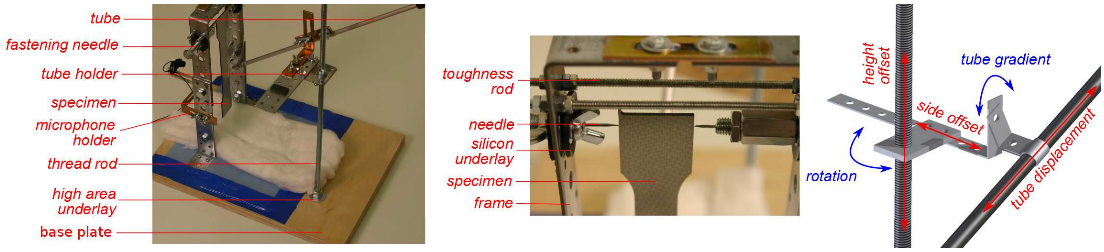

FIGURE 4. Description of acoustic testing device

2.**5**.2. *Pellet impact zone optimization.* Modal analysis was carried out prior the experiment. Results of the analysis were used to optimize pellet impact zone on specimen's surface. The goal of the optimization was to set the impact point into acoustic loop of specimen's shape. Additionaly, the results were used to find intersection of acoustic loops for two dominant natural modes 3070 Hz and 4008 Hz. Performing impacts in this intersection resulted in maximization of the spectral densities for dominant two natural modes. The analysis was calculated by finite element method (FEM) using ANSYS software. Finite element model was constructed by 8-node solid elements with linear shape function and with elastic constants 45.1 GPa for Young's modulus and 0.4 for Poisson's ratio. Pellet impact zone was selected to excite both natural modes 3070 Hz and 4008 Hz that had appeared regularly in frequency spectra during measurements of natural frequencies [8]. The impact point represented intersection of their calculated oscillation peaks. This point (100 mm from specimen's bottom edge close to its side edge) is shown in Fig. 6.

2.**6**. Three point bending

The decrement of elasticity modulus was measured using three-point bending test [9]. Custom-designed loading device [10] was employed for the test. Stepper motor with harmonic drive allowed displacement controlled experiments with accuracy 1 μm. The loadcell U9B (Hottinger Baldwin Messtechnik, GmbH) with loading range up to 100 N was used. The experiment was performed as displacement driven with maximal deflection value 1000 μm. The support span was 120 mm. The Young's modulus was calculated using the linear regression method from loading curves.

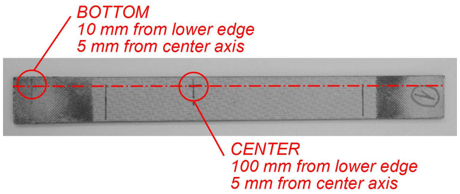

FIGURE 5. Pellet impact zones on specimen's surface

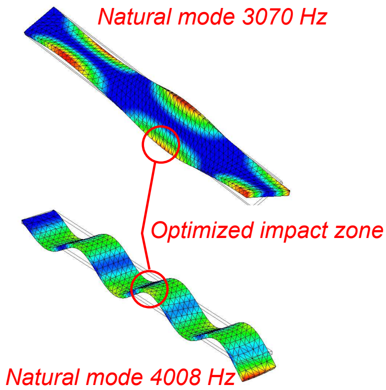

FIGURE 6. Natural modes for 3070 Hz, 4008 Hz and optimized impact zone

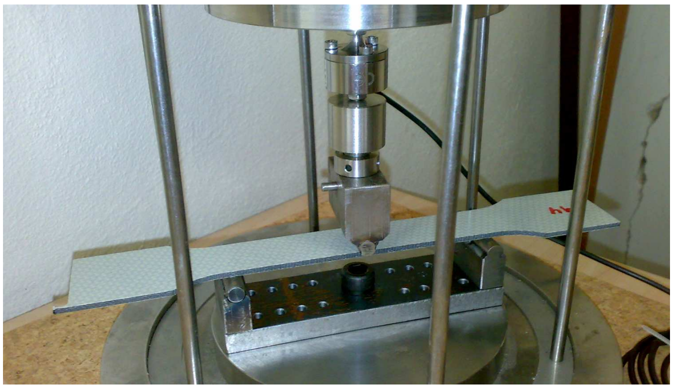

FIGURE 7. Experimental setup for three-point bending. Detail of the grips with load cell in the testing chamber

2.7. Photometric stereo

For the fatigue testing only the specimens with initial influenced zone diameter smaller than samples' width were used. Initial damaged area had to be surrounded by intact part of the specimen to avoid size effect in the experiment. Hereinbefore presented acoustic methods are not able to provide the reliable information about the dimensions of influenced zone. Therefore the optical method was employed to investigate the plastic deformations caused by impact loading.

Photometry is a method for 3D measurement of surfaces with relief [11]. It utilizes a relationship between depth of shadow, determined intensity of the light and surface normal orientation towards source of light. Advantage of methods incorporating this principle is their independence on distance between measured object and the measuring apparatus and scalable sensitivity suitable for measurement of relatively flat surfaces like impacted samples with dents of depth around 200 μm. This method was used only for evaluation of initial damage, not as a degradation parameter.

3. Results and discussion

All afore presented experimental procedures except ultrasound measurement showed a gradual degradation of the material. Module of elasticity computed from

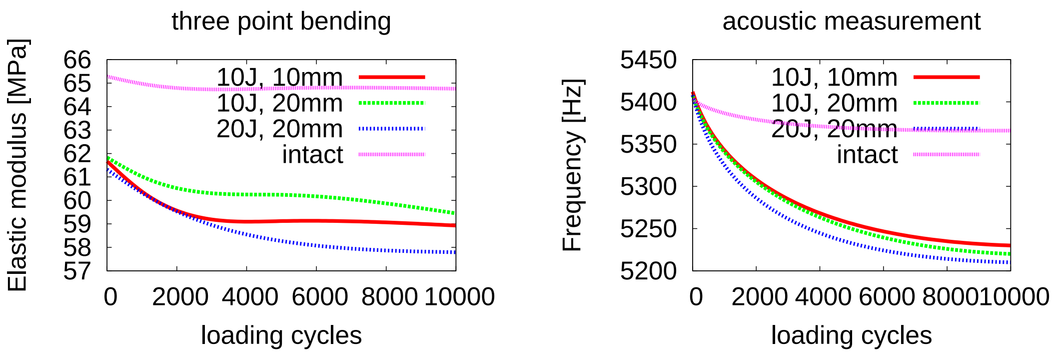

FIGURE 8. Material degradation assessed by bending and acoustic testing

three-point bending elasticity decreased without significant influence of impactor diameter. For the analysis the 13^{th} mode with natural frequency around 5000 Hz was chosen. In average natural frequency of the impacted specimens fatigued by 10000 decreased by 2.83 % and by 0.75 % for the intact one. Image processing tools, especially local thresholding was used for assessment of dent changes propagation from images obtained by photometric stereo. At both sides of the specimen the increase of influenced zone was observed but the method did not fully corellated with changes of material properties yet. To conclude, the data assessed using all presented measurements are suitable for evaluation of material degradation process in C/PPS composite during its fatigue live.

Acknowledgments

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