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ASSESSMENT OF THE POST-IMPACT DAMAGE PROPAGATION IN A CARBON-FIBRE COMPOSITE UNDER CYCLIC LOADING

OCENA NAPREDOVANJA POŠKODBE PO UDARCU PRI PONAVLJAJOČIH SE OBREMENITVAH KOMPOZITA Z OGLJIKOVIMI VLAKNI

Daniel Kytýř[1], Tomáš Fíla[2], Jan Šleichrt[2], Tomáš Doktor[1], Martin Šperl[1]

[1]Institute of Theoretical and Applied Mechanics, v.v.i., Academy of Sciences of the Czech Republic, Prosecká 76, 190 00 Prague 9, Czech Republic
[2]Czech Technical University in Prague, Faculty of Transportation Sciences, Department of Mechanics and Materials, Konviktská 20, 110 00 Prague 1, Czech Republic
kytyr@itam.cas.cz

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Carbon fibre in polyphenylene sulfide composites (C/PPS) became a popular material in the aircraft industry but its fragility and low impact resistance limits its application in primary aircraft structures. This study is focused on damage propagation in the laminated composites reinforced with carbon fibres. The damage may be inflicted during the ground maintenance, by an inflight bird strike or during a flight in severe meteorological conditions (heavy storms). The initial damage was created by a drop-weight out-of-plane impact using a spherical indenter. The response of the material was analysed by monitoring the impacted zones and their propagation history. The influenced area and specimen thickness in the centres of indents were chosen as the degradation parameters. The post-impact damage propagation induced by cyclic loading was assessed using a custom-designed computer-controlled laser-profilometery device. Both the upper and lower profiles of the specimen were scanned during the interruptions of the fatigue test. Global deformation was described with an analytically determined centroidal-axis curve. Local topography changes were obtained with a subtraction of this curve. Surface-deformation maps were created and used for a demonstration of the damage propagation in the specimen.

Keywords: carbon-fibre composites, post-impact damage, laser profilometry

Ogljikova vlakna v kompozitih iz polifenilen sulfida (C/PPS) so postala priljubljen material v letalski industriji, toda njihova krhkost in slaba odpornost proti udarcem omejujeta njihovo uporabo v primarnih letalskih konstrukcijah. Ta raziskava se osredinja na napredovanje poškodbe na laminiranih kompozitih, ojačanih z ogljikovimi vlakni. Poškodba lahko nastane med vzdrževanjem na tleh, pri trčenju s ptico med letom ali med letom v hudih vremenskih razmerah (huda nevihta). Začetna poškodba je bila narejena z udarno pregibnim preizkusom s kroglastim vtiskovalcem. Odziv materiala je bil analiziran z opazovanjem območij udarca in potekom napredovanja. Prizadeto območje in debelina vzorca v področju vtiska sta bila izbrana kot parametra degradacije. Napredovanje poškodbe po cikličnem obremenjevanju po udarcu je bilo ocenjeno s po meri oblikovane računalniško vodene naprave za lasersko profilometrijo. Zgornji in spodnji profil vzorca sta bila skenirana med prekinitvami preizkušanja utrujenosti. Celotna deformacija je bila opisana z analitično določeno krivuljo težiščnice. Lokalne spremembe topografije so bile dobljene z odštetjem te krivulje. Ustvarjeni videzi deformacije površine so bili uporabljeni za prikaz napredovanja poškodbe na vzorcu.

Ključne besede: kompoziti z ogljikovimi vlakni, poškodba po udarcu, laserska profilometrija

1 INTRODUCTION

The design and safe operation of lightweight structures, especially in the aviation industry, is particularly important and challenging due to the inauspicious load spectra composed of a large number of low-amplitude cycles and sudden impacts[1]. Low-amplitude cycles are caused by aerodynamic loads and engine vibrations. Wayward strikes may be inflicted during the ground maintenance, by inflight collisions (bird strikes) or severe meteorological conditions (heavy storms).

The damage-tolerance approach commonly used in aerospace engineering requires a comprehensive knowledge of the material-degradation process and a reliable prediction of a structure safe life[2]. The thermoplastic composites commonly used for these purposes allow an application of an optimised manufacturing technology[3,4]. An application of a polymeric matrix lowered the tendency towards brittle behaviour (common for carbon-fibre composites) and exhibited the advantages of high chemical resistivity, insensitivity to moisture, good fatigue performance[5,6] and recyclability.

Micromechanical modelling of the composites with imperfections[7] sufficiently describes the degradation process. However, the material models based on the X-ray computed tomography of the specimen representing the material at the macroscopic level including a complex microstructure could not be evaluated using the finite-element simulations with the plasticity applied due to the computational complexity and enormous memory requirements[8]. The presented work aimed to extend the range of non-destructive testing (NDT) techniques comprising the lock-in thermography[9] or the modified-impulse excitation technique[10].

2 MATERIALS AND METHODS

2.1 Specimen description

The base material, a carbon-fibre/polyphenylene sulphide (C/PPS) composite manufactured by Letov letecká výroba, s. r. o., was delivered as plates with a thickness of (2.5 ± 0.05) mm. The material consists of quasi-isotropic 8-ply carbon fabric with its volume fraction higher than 90 %, bonded with a thermoplastic matrix. The surface is covered with a thin glass-fibre cloth protecting the core against mechanical and chemical influences. The final specimens with a rectangular shape with the dimensions of 250 mm × 25 mm were cut from the plates using a water-jet cutter.

2.2 Initial damage

The first step of the experimental procedure was to inflict the initial damage to the specimens under controlled conditions. A drop tower designed within project SGS12/163/OHK2/2T/16 with the maximum impact energy of 50 J was used. The strike was carried out using a spherical indenter with a diameter of 20 mm and the energies of (10, 20 and 15) J on (30, 50 and 70) % of the length of the samples. The imprints of the diameter in the range of millimetres and the depth in the range of tens of micrometers then occurred.

2.3 Fatigue loading

For a life-cycle assessment the specimens were cyclically loaded using a Mikrotron (Russenberger Prüfmaschinen, AG) resonant testing machine (**Figure 1**). To ensure the loading at the chosen stress level (33 % of the tensile strength) the mean loading-force value of 6 kN and the amplitude of 5 kN were set. A sinusoidal force was applied in the force-driven experiments.

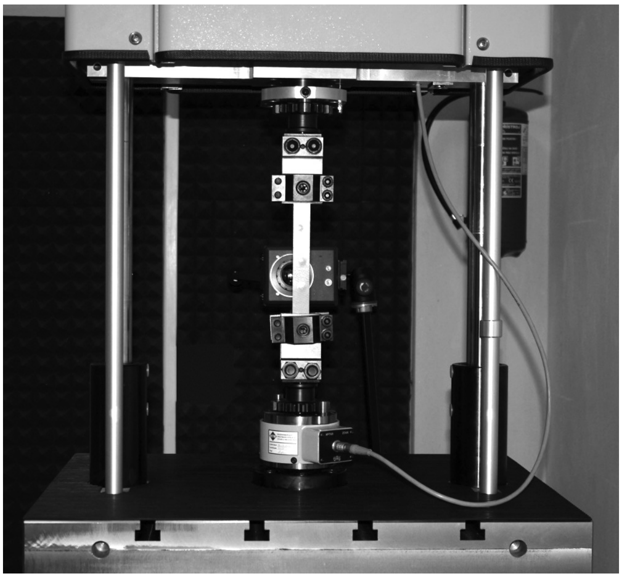

Figure 1: Experimental device for dynamic loading
Slika 1: Eksperimentalna naprava za dinamično obremenjevanje

Due to a relatively high testing frequency (approximately 75 Hz), the experiment was monitored with a thermal imaging camera SC7600 (FLIR Systems, Inc.). To prevent exceeding 50 % of the glass transition temperature the specimen temperature was held at maximally 60 °C. At the same time, the lower frequency limit was set in order to avoid a specimen rupture[11]. The fatigue experiment was interrupted six times at the predefined numbers of cycles to perform profile scanning.

2.4 Profile measurement

To obtain the information about damage propagation during the life cycle, a set of profilometery experiments was performed. A custom-designed scanning device equipped with laser scanner ScanControl LLT2600-25 (Micro-Epsilon Messtechnik) depicted in **Figure 2** was used for this purpose. The device allowed us to measure the line profiles with the length of 20–40 mm, defined by 1024 measured points. The altitude resolution of the scans was 4 μm. The scanner was mounted on a motorised computer-controlled single-axis linear stage with the minimum incremental motion of 10 μm and the on-axis accuracy of ± 0.5 μm. One scanning sequence took approximately 15 minutes.

2.5 Damage-propagation assessment

The changes in the impact depth, the sample thickness and the area of influenced zones were chosen as the degradation parameters. The automatic procedure for a surface reconstruction (**Figure 3**) and profile-change assessment was carried out using the tools developed in the MATLAB (Mathworks, Inc.) computational environment. The variable position of the samples in the scanning area required the use of the corner detection

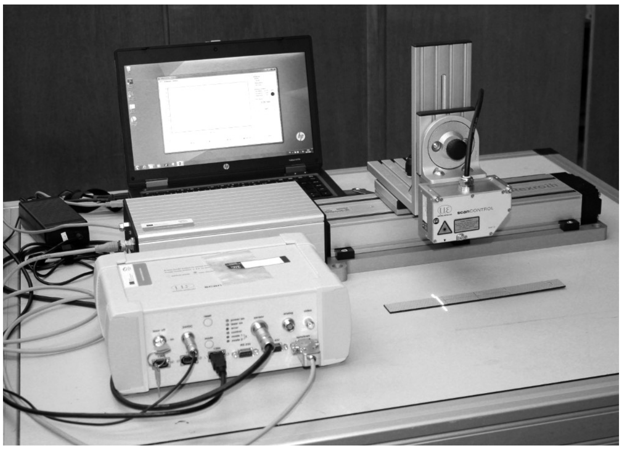

Figure 2: Custom-designed computer-controlled profilometery device equipped with a ScanControl LLT2600-25 laser scanner
Slika 2: Po meri oblikovana računalniško vodena naprava za profilometrijo, opremljena z laserskim optičnim bralnikom ScanControl LLT2600-25

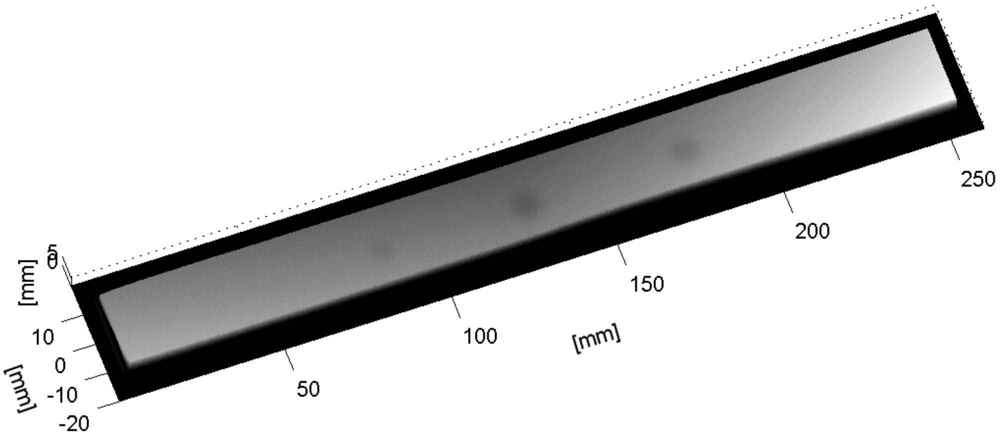

Figure 3: Reconstruction of the sample surface based on laser triangulation
Slika 3: Rekonstrukcija površine vzorca, ki temelji na laserski triangulaciji

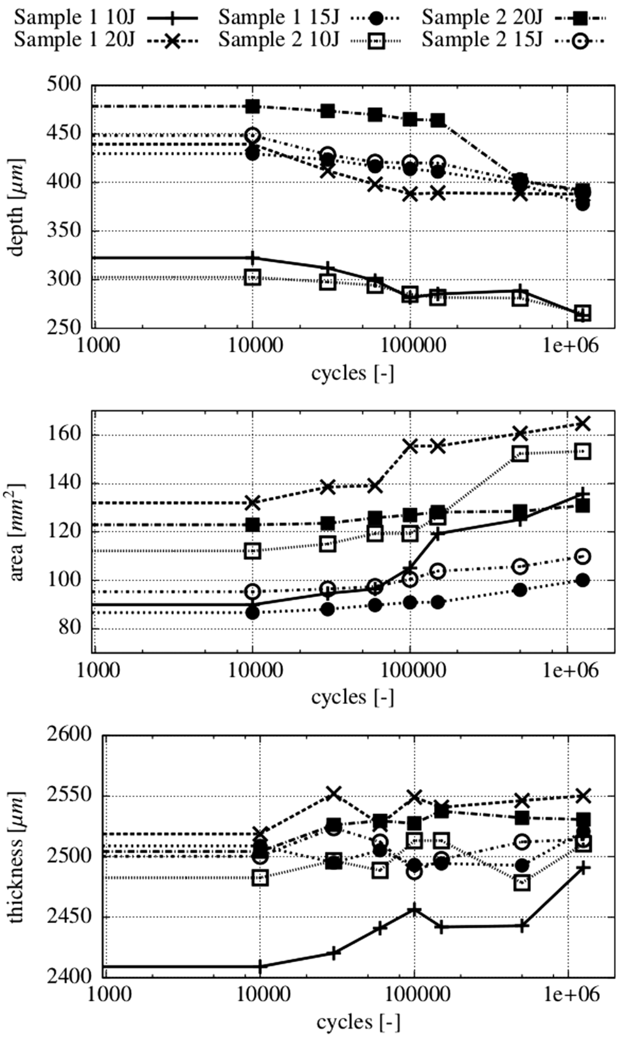

Figure 4: a) Increase in the influenced zones, b) the maximum depth of the impact depression and c) the thickness of the sample plotted against the number of loading cycles
Slika 4: a) povečanje obsega prizadetega območja, b) maksimalne globine udrtine ter c) debelina vzorca glede na število ciklov obremenitve

algorithm based on the altitude threshold to detect the specimen boundaries in the captured data. Transformation functions were obtained and the objects were transformed into a unitary coordination system.

Divergence of the laser beam was taken into account for the real-altitude matrix estimation and the blur of the edges caused by the same effect was reduced with gradient filters. The curvature of the surfaces was not caused only by the local impact zones but also by the overall bending of the samples due to a combination of the initial impact damage and cyclic loading. A piecewise continuous second-order curve (the centroidal axis) was fitted and set as a new reference level. Then the altitude matrices were updated. On the straightened surfaces, the local impacted zones were quantified (area, maximum depth) using the data-registration procedure. From the subtraction of the upper and lower profile, the change in the sample thickness was obtained.

3 RESULTS

Based on the reconstructed profiles from the laser measurements, the influenced zones were identified on the basis of thresholding. In the areas of interest, the impact depression depth and the local thickness were assessed. Propagation of the chosen degradation parameters on two selected samples for several distinct impact levels is depicted in **Figure 4**.

Damage propagation exhibits similar evolution on different tested samples. The most significant parameter was the maximum depth of the impact on the impacted side. The initial depth corresponds to the strike energy, while later the depth decreases with the increasing number of the loading cycles. The area of influenced zones grows with the number of the loading cycles but, surprisingly, the initial areas were not proportional to the strike energy. The area of damaged zones inflicted by lower energy impacts also showed a faster increase. The changes in the thickness of the samples due to the influenced zones were negligible as the differences in the thickness were only two or three times higher than the noise.

4 CONCLUSIONS

The presented study describes the possibility of a time-lapse profilometery measurement for an evaluation of the post-impact damage propagation in a C/PPS composite under cyclic loading. The chosen parameters (the area of impacted zone, the maximum depth and the sample thickness) provide the information about damage accumulation in the material. Generally, laser profilometery is a suitable method for the NDT testing and evaluation of the surface damage. The described modified method is applicable to bigger components and structures. With respect to our measured data, the reliability of the method was reduced by the resolution of the available laser scanner.

Acknowledgements

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