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IDENTIFICATION OF DAMAGED ZONES IN C/PPS SPECIMENS SUBJECTED TO FATIGUE LOADING BASED ON HIGH-RESOLUTION THERMOGRAPHY

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Abstract. In this study high resolution thermography is used for identification of damaged zones in Carbon fiber/polyphenylene sulfide (C/PPS) long fiber composite specimens with induced impact damage subjected to tensile fatigue loading. Image processing techniques were applied on thermographs from all loading cases to obtain segmented images of the damaged location that were then used for calculation of the heated area. Results show that the considered method can be used to identify heated area in the vicinity of damage with high confidence at low number of cycles where no significant fatigue effect is present in the material.

Keywords: fatigue, damage, long fiber composite, C/PPS, thermography.

1. Introduction

Composites with different matrix materials reinforced by short or long fibers have been widely used as structural materials thanks to their favorable mechanical properties (particularly relative stiffness and strength) for several decades. One of very popular composite compounds widely used in aviation industry consists of polyphenylene sulphide (PPS) matrix and carbon fiber reinforcement. The material is commonly used for production of both external and internal aircraft components because of its excellent mechanical properties, chemical resistance to aerospace fluids, low density and good resistance to heat and flames [1]. Micrograph of damaged composite structure after material failure is depicted in figure 1.

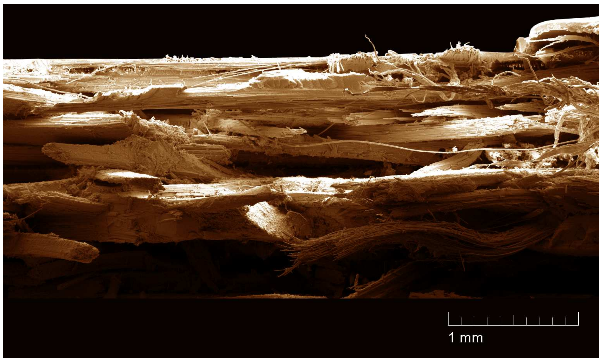

Figure 1. Detail of damaged structure obtained by scanning electron microscope, the plies are consisted of yarn with individual 5 μm fibres.

Still, application of this material in airframes is limited by its relatively low impact resistance and fragile behavior that have to be thoroughly investigated before its operational deployment [2]. In the life-cycle of an airframe, damage from impacts may be inflicted during flight or ground maintenance. This in combination with unique nature of composites and high cycle fatigue may lead to unexpected failure due to damage accumulation in the material's microstructure [3]. In this study high-resolution thermography has been used to observe dynamically loaded damaged specimens in order to quantify thermal characteristics of the damaged area and to evaluate suitability of considered approach for NDT inspection/damage tolerance analysis [4–6]. Thus, primary goal of this study was to identify lowest possible stress level for reliable assessment of the damage in low number of loading cycles.

2. Materials and Methods

2.1. Specimen Description

The C/PPS material used in this study consists of 8-ply of carbon fabric with volume fraction of fibres approximately 60 %, overall density 1.35 g · cm^{-3} and quasi-isotropically distributed fibres. Surface of the samples was covered by thin glass fibre cloth protecting the core against UV light, surface damage and chemical influences. Set of eight dog bone shaped specimens were prepared using numerical controlled water jet cutter from two plates of C/PPS material (dimension 160 × 160 mm) with thickness 2.5 ± 0.1 mm. Overall length of specimens was 160 mm. Distal part with width 25 mm was used for best possible fixation in mechanical grips whereas central part with length 105 mm and width 20 mm was subjected to the initial loading and thermographically investigated.

2.2. INITIAL DAMAGE

Before dynamic loading the specimens were subjected to impact loading to impose initial damage under controlled conditions using instrumented drop tower. Experimental setup with maximal impact energy 50 J was used in configuration with steel spherical impactor having diameter 15 mm. Impact energy of 15 J was set to inflict initial damage in the central part of the sample leading to imprint diameter in range of millimeters and depth in range tens of micrometers. The geometrical characteristics of imprints were identified using laser profilometry method [7].

2.3. EXPERIMENTAL SETUP

For the investigation of thermal response to the mechanical loading Mikrotron (Russenberger Prüfmaschinen, Germany) resonant testing machine was employed. Loading was performed in tensile mode at four stress levels with mean load 4.5, 5.0, 5.5, 6.5, 8.0 kN and amplitude 2.0, 3.0, 4.0, 4.5, 5.0, 6.0 kN in sinusoidal cyclic force. Testing frequency was approximately 75 Hz. Highest stress level did not exceed 35 % of tensile strength of the material and fully elastic behaviour during loading cycles was assumed. One of damage degradation parameter obtained from resonant excitation is cycle dependent decrease of natural frequency. According to our previous study eigenfrequency decrease lower than 0.05 % indicates no damage inflicted in the material's microstructure. Over the whole testing campaign this level was not exceeded as can be seen from graph of natural frequencies plotted against number of cycles (figure 2).

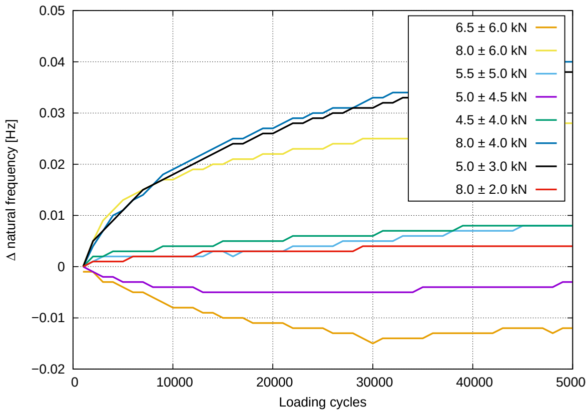

FIGURE 2. Variation of natural frequency as a function of number of cycles.

The test was performed at constant room temperature 22 °C. Loading scene was observed using scientific-grade thermal imaging camera SC7650 (FLIR Systems, USA). The device is equipped with InSb cooled sensor with pixel pitch 15 μm and resolution 640 × 512 px. The device allows acquisition of images in temperature range −20 to 300 °C with full frame sampling frequency 100 Hz. In this work full frame resolution and 0.5 Hz acquisition frequency was used. Control of the camera and acquisition of thermographs was performed using GigE interface. Experimental setup is depicted in figure 3.

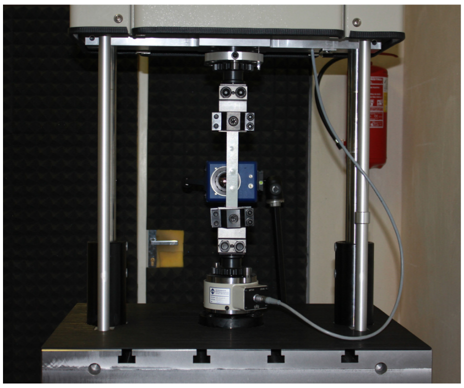

FIGURE 3. Experimental setup for thermographical observation of dynamic loading.

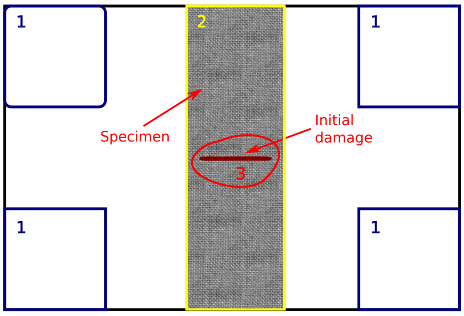

FIGURE 4. Distribution of ROIs in thermograph for segmentation and area calculation: 1) background temperature, 2) specimen temperature, 3) heated area.

2.4. IMAGE PROCESSING PROCEDURE

Thermographs were subjected to image processing procedures in order to identify the damaged zone and to calculate the heated area in its vicinity. Adaptive identification technique based on the median value of the background (blue areas in figure 4) was used for differentiation of the sample and background. Median of specimen's temperature was then found and area with temperature higher than 105 % of the median temperature was subjected to investigation (red area in figure 4). Standard morphological opening and closing procedures with circular structuring element were applied on the identified heated areas to improve accuracy of impacted area calculation. In result all holes in the identified area smaller than 3 px^2 were morphologically closed and areas smaller than 10 px^2 were neglected from the calculation. Visualisation of a series of thermographs subjected to investigation using image processing techniques is shown in figure 5.

3. RESULTS

During the thermographically observed experiments it has been found out that normalized peak temperature (temperature of specimen relative to ambient temperature) converges to constant value in less than 50 000 loading cycles. In figure 6 dominant influence of the amplitude compared to mean value of applied load to the maximal temperature is clearly visible. In case of the highest loading level temperature of the specimen reached absolute value of 45 °C corresponding to less than 50 % of the material's glass transition temperature. Therefore negative thermal effects influencing the material properties (particularly the assumed elastic behavior) during the test were avoided.

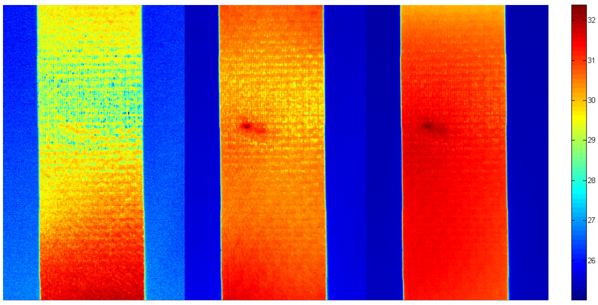

Figure 5. Example of a series of acquired thermographs showing heating of the damaged zone during cyclic loading at 1 s (left), 32 s (middle) and 200 s (right); temperature scale is in $^\circ C$.

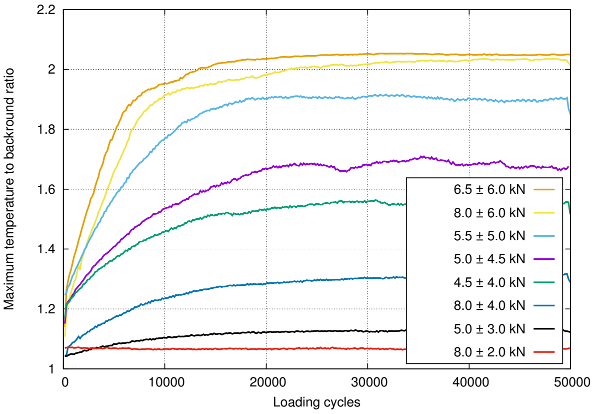

Figure 6. Ratio of specimen to ambient temperature as a function of number of cycles.

Threshold temperature higher than 105 % of average specimen temperature (calculated from the yellow area in figure 4) was chosen for identification of the local damaged zone. According to acquired results significant increase of the temperature in damaged zone became observable after only a few hundred of loading cycles. After that peak temperature in the damaged zone rose sharply together with average temperature in the entire volume of the samples. This average temperature reached its maximum equal to temperature after approximately 10 000 loading cycles yielding the thermal footprint of the samples homogeneous. Hence higher number of loading cycles was unnecessary for our study. Identified damaged zones for all loading cases are depicted in figure 7.

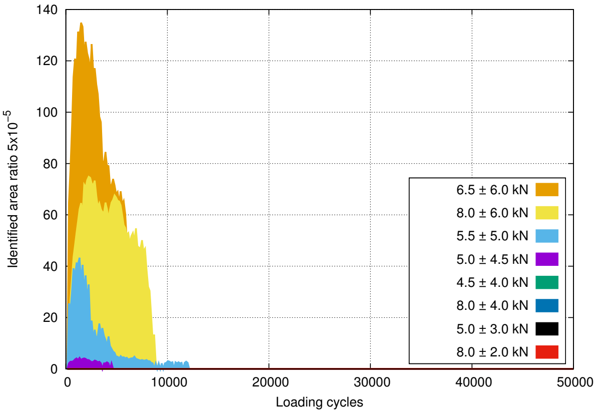

Figure 7. Variation of identified heated area in the vicinity of damage as a function of number of cycles.

It can be seen that minimal loading level 5 ± 4.5 kN was sufficient for reliable identification of the damaged zone in the vicinity of impact due to its apparent heating. Detailed plot of identified heated area in the vicinity of damage and median temperature of specimens for two representative loading cases is shown in figures 8 and 9. Here increase of the loading to 6.5 ± 6 kN shows significant increase of the relative heated area (ratio of identified heated area in the vicinity of damage to total area of specimen) of magnitude more than 30 times. This together with the fact that in all cases number of loading cycles lower than 10 000 was sufficient for identification of the influenced zone indicates that the proposed method is suitable for non-destructive inspection of C/PPS long-fiber composites.

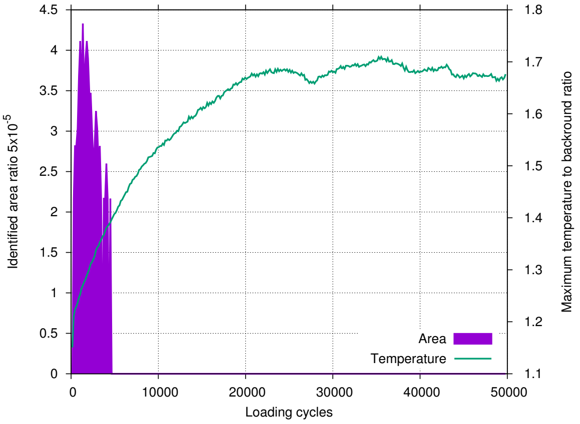

Figure 8. Evolution of identified heated area during mean temperature of specimen during 5 ± 4.5 kN loading.

4. Conclusions

It can be seen that in majority of loading cases the material exhibits consolidation and hardening in the first 50 000 cycles. For the two cases where combination of mean force and amplitude causes damage accumulation image processing methods have been applied on thermographs to obtain segmented images of the damaged location. From the segmented

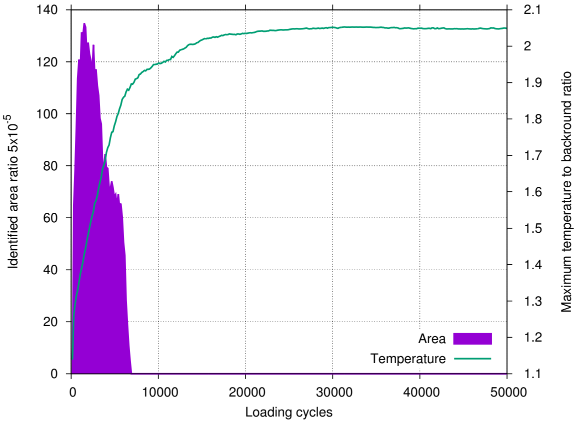

Figure 9. Evolution of identified heated area during mean temperature of specimen during 6.5 ± 6 kN loading.

images heated areas were calculated together with specimen/background temperature ratio and plotted against number of loading cycles. It is apparent that heated area in the vicinity of damage can be identified with high confidence at low number of cycles (10 000) where no significant fatigue effect is present in the material. The considered inspection method is thus suitable for NDT inspections or damage tolerance analysis.

Acknowledgements

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