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3D photothermal imaging of subsurface damage evolution in fibrous composite materials due to fatigue loading

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Abstract

In this study, we present results from 3D photothermal imaging of the damage evolution in fibrous composite materials due to fatigue loading using the virtual wave concept. We apply pulsed thermography during step-wise fatigue loading for a carbon fiber-reinforced polymer sample, which contains a central open hole. In addition, we discuss the influence of the ambient conditions from in-situ photothermal testing on the virtual wave signal. Comparison with 3D computed tomography measurement data shows very good agreement with the thermographic reconstructions. Thermography has the advantage over other methods that it allows inline measurements directly on the tensile testing machine.

1. Introduction

Carbon fiber-reinforced polymers (CFRPs) are increasingly used in the aerospace industry due to their excellent strength-to-weight, as well as stiffness-to-weight-ratio. Due to their heterogeneous material composition, CFRPs exhibit complex damage behavior under fatigue loading application. Degradation phenomena in CFRP generally result in reduced load carrying capacity, making proper in-service characterization essential.

In this study, we perform pulsed thermography (PT), a subcategory of optical stimulated thermography (OST), during step-wise fatigue loading in tensile-tensile configuration, aimed to monitor the subsurface damage progression of the observed sample in-situ. For post-processing the generated temperature signals from PT, we apply the so-called virtual wave concept (VWC), which is a two step evaluation procedure [1]. In the first step, the VWC transforms a surface temperature signal pixel-wise (locally) into an "acoustic" virtual wave signal. Then, in the second reconstruction step, the VWC accounts for transversal heat flow. This is highly relevant for anisotropic composite materials, because they have a large ratio of in-plane to through-plane thermal diffusivity. In recent studies, the VWC has been extended for the application to anisotropic composites and used for 3D photothermal imaging of an impact damage in anisotropic media [2].

2. Theory

The transformation between surface temperature signal and virtual wave signal is given in discrete form for one spatial cross-section with pixel number q as linear matrix equation [2]:

$$\mathbf{T} = \mathbf{K}\mathbf{T}_{\mathsf{virt}}, \tag{1}$$

with the discrete surface temperature signal $\mathbf{T} \in \mathbb{R}^{N_{\mathsf{t}} \times q}$, the discrete transformation kernel $\mathbf{K} \in \mathbb{R}^{N_{\mathsf{t}} \times N_{\mathsf{tv}}}$ and $\mathbf{T}_{\mathsf{virt}} \in \mathbb{R}^{N_{\mathsf{tv}} \times q}$ as discrete virtual wave signal. Herein, N_{t} and N_{tv} are the number of time steps for the temperature signal and for the virtual wave signal, respectively. Using $t_k = k\Delta_t$ and $t'_j = j\Delta_{t'}$, with the running variables $k = \{0, 1, 2, ..., N_{\mathsf{t}} - 1\}$ and $j = \{0, 1, 2, ..., N_{\mathsf{tv}} - 1\}$, the component notation of the discrete kernel $\mathbf{K}$ is given as:

$$K(k, j) = \frac{\tilde{c}_{33}}{\sqrt{\pi \Delta_{\mathsf{Fo}} k}} \exp\left(-\frac{\tilde{c}_{33}^2 j^2}{4\Delta_{\mathsf{Fo}} k}\right), \tag{2}$$

with the dimensionless speed of sound through plane $\tilde{c}_{33} = c_{33}\Delta_t/\Delta_z$, the discrete Fourier number $\Delta_{\mathsf{Fo}} = (\alpha_{33}\Delta_t)/\Delta_z^2$, the thermal diffusivity through plane α_{33}, the resolution through plane Δ_z and the temporal resolution $\Delta_t = \Delta_{t'}$. Since we deal with an severely ill-posed inverse problem, we apply the alternating direction method of multipliers (ADMM) for regularization.

3. Photothermal setup

In this study we investigate a carbon fiber-reinforced polymer (CFRP) sample, made from prepreg tape material CYCOM G40-800/5276-1, with a multidirectional stacking sequence. The observed sample has a central open-hole, which was introduced by conventional drilling. Fatigue loading resulted in the appearance of material damage in the region of the hole due to the stress concentration. The experimental setup is given in Fig. 1a) and consists of an IR camera, two flash lamps and a servo-hydraulic fatigue testing unit. We applied photothermal testing after subjecting certain loading cycles to the sample, to monitor the subsurface damage progression. For photothermal testing, the sample was single pulse heated with flash lamps (type PB-G6000) and the corresponding surface temperature signal was recorded with the IR camera FLIR X8400sc in the pulse-echo configuration. The transversal resolution was $\Delta_x = \Delta_y = 144$ μm and the temporal resolution was $\Delta_t = 0.02$ s.

4. Results and discussion

We show exemplary results from photothermal reconstruction during step-wise fatigue loading, to demonstrate imaging of the material damage evolution with the post-processing tool VWC. From the measured surface temperature signal $\mathbf{T}$, we obtain the corresponding virtual wave signal $\mathbf{T}_{\text{virt}}$, by calculating the inverse of the linear matrix Eq. 1. The spatial resolution through plane for the virtual wave signal was $\Delta_z = 70$ μm.

Fig. 1b) exemplary depicts a mean virtual wave image, evaluated for the depth sequence of (560:Δ_z:840) μm, which was generated from photothermal testing after the application of 80·10^3 fatigue loading cycles. The mean virtual wave image clearly shows a material damage due to the applied mechanical loading sequence. Fig. 1c) gives contour plots from photothermal reconstruction, showing the defect evolution during step-wise fatigue loading for the observed open hole sample. The contour plots with $\mathbf{T}_{\text{virt}} = 20$ K were calculated from mean virtual wave images, for numerous loading cycles, with the depth sequence (560:Δ_z:840) μm. The damage is initiated at the position of the open hole and propagates through the material as the number of cycles increases. In this study, we also discuss the influence of the ambient conditions, for instance convection, from in-situ photothermal testing on the virtual wave signal.

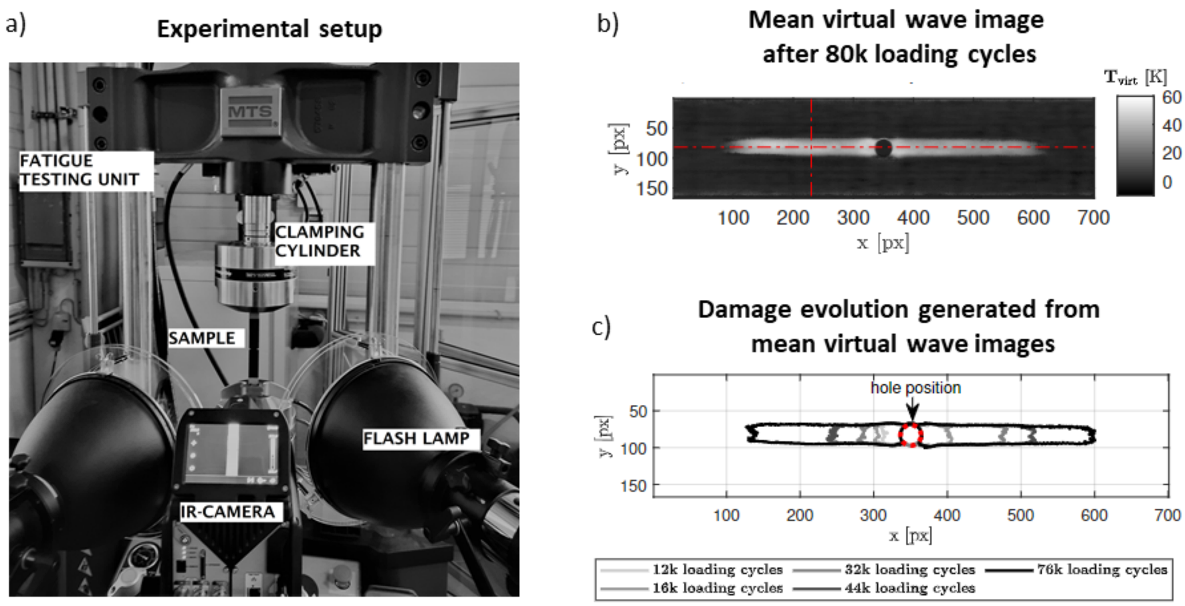

Fig. 1. *Exemplary experimental results: a) Photothermal setup during step-wise fatigue loading. b) Reconstructed mean virtual wave image after 80·10^3 loading cycles, evaluated for the depth sequence (560:Δ_z:840) μm. c) Contour plots with $\mathbf{T}_{virt}$ = 20 K, generated from mean virtual wave images, showing the defect evolution at different loading sequences.*

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