NDT&E International 83 (2016) 114–122

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Investigation on the damage evolution in the impacted composite material based on active infrared thermography

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ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form
15 June 2016
Accepted 21 June 2016
Available online 21 June 2016

Keywords:
Impacted composite laminate
Damage evolution
Fatigue test
Active infrared thermography
Infrared image processing

ABSTRACT

A novel method was proposed to investigate the damage evolution of the impacted composite laminate using active infrared thermography in this work. This method was comprised of the following procedures. Firstly, the infrared images, containing the damage information under different fatigue cycles, were obtained through fatigue test and damage detection test. Then, the damage area of the impacted composite laminate being inspected under different fatigue cycles was acquired through such infrared image processing as image enhancement, image segmentation and quantitative identification. Finally, an expression, indicating the relationship between the fatigue cycles and the damage area, was fitted by the least square method. Four specimens were implemented to validate the effectiveness of the proposed method via the proposed procedures. The results indicate that the proposed method can effectively reveal the damage evolution. I.e. the expressions can be accurately fitted and the corresponding accuracy can be as high as 0.98186, 0.95067, 0.9797 and 0.99316 respectively.

1. Introduction

Composite materials have been used extensively in a wide range of aerospace, such as airplane, missile, rocket and artificial satellite, etc. in the past several decades due to the advantages of excellent strength and stiffness to weight ratios over many other types of materials [1–4]. However, the composite materials are unavoidably exposed to the low velocity impact caused by dropping tools, collisions with birds, strong gales and stones [5], which generally leads to such barely visible impact damage (BVID) as delamination, de-bonding, matrix cracking and fiber breakage in the composite materials and remarkably affects the performance of composite materials [6–8]. In this case, continuing to employ the impacted composite materials will cause the impact damage expansion, which extremely threatens the safety and reliability of composite structure and ultimately results in the rupture of the structure. Thus it is significant to explore an effective method to reveal the damage evolution in the impacted composite materials to ensure the composites to meet the demands of applications.

Numerous techniques have been proposed to reveal the damage evolution [9–12]. The most common methods are based on local stress strain [9], fracture mechanics [10,11] and damage mechanics [12]. But the above-mentioned methods require abundant time.

Infrared thermography possesses superior performances such as high-speed, large area inspection and intuitional results, etc. in detecting damage [13–18] and gradually has developed into a novel method to reveal the damage evolution [19–21]. In 1984, Milne and Reynolds [22] proposed the infrared thermography as a nondestructive method and pointed out its ability to inspect defects in the materials with great speed. As a consequence, many scholars started to investigate this nondestructive testing (NDE) technique by building finite element model to analyze the thermal conductivity [23–25]. Then, infrared thermography was proven successful to detect and characterize the damage within the materials [26–29]. Afterwards, infrared thermography was applied to reveal the damage evolution as its application proceeded [19–21,30,31]. In summary, infrared thermography presented in the above works available was implemented to reveal the damage evolution by monitoring the surface temperature of the specimen using the infrared camera (IR). Due to the relationship between the damage and the temperature, damage evolution of the materials can be concluded by analyzing the surface changeable temperature of the object. But this method has high demands for the accuracy of the IR and for the low thermal diffusivity of the materials, especially for the composites.

The objective of this work is to provide a novel method to reveal damage evolution of the impacted composite materials based on the active infrared thermography. To this end, combining the appropriate infrared image processing methods, infrared thermography was applied to quantitatively evaluate the damage area in the specimen. On this basis, the damage area in the specimen

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http://dx.doi.org/10.1016/j.ndteint.2016.06.008
0963-8695/

under different fatigue cycles was obtained. Then, the quantitative expression, indicating the damage evolution of the impacted composite laminate, was fitted using the least squares method. The proposed method was validated by several specimens, showing excellent performance.

2. Theory of the infrared thermography detection

Active infrared thermography system mainly consists of the computer, IR and exciting source. The active infrared thermography mechanism is indicated in Fig. 1. Exciting sources release impulse thermal-wave or ultrasonic thermal-wave to excite the specimen, if there were defects in the specimen, due to the thermal conductivity difference between the defects and the specimen material, the changeable temperature of the surface of the specimen will be generated and recorded by IR. The infrared images recorded by the IR contain the information of the defects, thus, the quantitative evaluation of the defects can be carried out by analyzing the infrared images [17,18].

3. A novel quantitative evaluation of the defect by infrared thermography

3.1. Image enhancement procedure

The infrared images obtained by IR have some problems of high noise and low contrast due to the fixed pattern noise, radial distortion and properties of the specimen surface, etc. and these problems seriously affect the quantitative identification of the defects. In this work, the improved nonlinear diffusion partial differential equation algorithm is proposed to remove the noise and improve the contrast.

The substance of conventional partial differential equation used for infrared image enhancement is to solve the thermal diffusion equation, as showed in Eq. (1).

$$\frac{\partial I(x,y,t)}{\partial t} = \mathrm{div}(\nabla I) = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2}$$
$$I(x,y,0) = I_0(x,y) \tag{1}$$

Where $I_0(x, y)$ is the raw infrared image, $I(x, y, t)$ is the infrared image at t moment in thermal diffusion. Solving Eq. (1) yields

$$I(x,y,t) = I_0(x,y) * G_t(x,y) \tag{2}$$

with $G_t(x,y) = \frac{1}{4\pi t}\exp\left(-\frac{x^2+y^2}{4t}\right)$ and "*" is the convolution operation.

Conventional partial differential equation destroys the edge of infrared image, though it can effectively remove the noise. For the sake of implementing to protect the edge while removing the noise, non-negative edge function $g(r)$ with the characteristic of monotone decreasing is proposed by Perona [32] and new thermal diffusion equation is showed as follows.

$$\frac{\partial I(x,y,t)}{\partial t} = \mathrm{div}\left[g(\nabla I)\nabla I\right] \tag{3}$$

Eq. (3) is generally called as the P-M equation. In the image processing, it is need to build a $g(r)$ to estimate the edge point. The most frequently used edge function is showed in Eq. (4).

$$g(r) = \frac{1}{1+\left(\frac{r}{K}\right)^p} \qquad p = 1, 2 \tag{4}$$

Where the parameter K is a constant and used for controlling the declining rate of the edge function.

In the P-M equation, the two edge functions, most frequently used, are showed in the following equations.

$$\mathrm{PM1:}\ g(r) = \frac{1}{1+\left(\frac{r}{K}\right)^2} \tag{5}$$

$$\mathrm{PM2:}\ g(r) = \exp\left(-\left(\frac{r}{K}\right)^2\right) \tag{6}$$

In Eqs. (5) and (6), selecting appropriate value of K can enhance the edge of the defects. However, when the image contrast is low, there is a disadvantage of removing the noise using P-M equation. To solve this problem, a new $g(r)$ is proposed in this work, as showed in Eq. (7).

$$g(r) = \begin{cases} \left[1-(r/K)^2\right]^2, & |r| \le K \\ 0, & \text{else} \end{cases} \tag{7}$$

3.2. Quantitative evaluation procedure

The damage area directly affects the safety of structures such as airplane, missile, rocket and artificial satellite, etc. On this account, the effective detection and the quantitative identification are required when the active infrared thermography is applied to detect

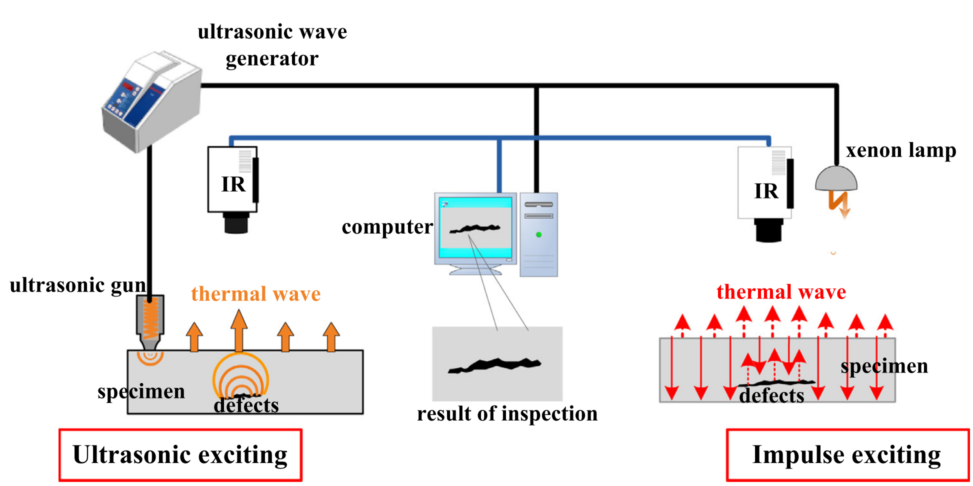

Fig. 1. The active infrared thermography system.