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Theoretical and experimental study on carbon/epoxy facings-aluminum honeycomb sandwich structure using lock-in thermography

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ABSTRACT

Carbon/epoxy facings-aluminum honeycomb sandwich structure (C/E FAHS) is widely used in aircraft and aerospace with the merit of high-specific strength, high-specific modulus and lightweight. However, layered debonding as the main defect type of C/E FAHS affects the material performance seriously. Therefore, in this present study, lock-in thermography was introduced to detect debonding defects of C/E FAHS. A three-dimensional finite element model (FEM) of this material stimulated by sinusoidal excitation signal was built. The influence of modulation parameters (i.e. modulation frequency, light power intensity, and the number of excitation cycles) and the structural parameters of carbon/epoxy facings were analyzed. Furthermore, C/E FAHS specimens were detected by lock-in thermography. The experimental study on the influence of modulation parameters and structural parameter was carried out. Results demonstrated that lock-in thermography was an effective method to detect debonding defects of C/E FAHS.

1. Introduction

Carbon/epoxy facings-aluminum honeycomb sandwich structure (C/E FAHS) is a special type of composite material. It is made of two high-strength, thin C/E facings and a lightweight aluminum honeycomb core. This material has the merits of high-specific strength, high-specific modulus and lightweight, which lead to wide application in the field of aircraft and aerospace, satellite fairing is a classic example. The debonding defects are stratified between the film and the aluminum honeycomb, and these defects can appear in several ways, during the fabrication stages, subsequent machining, or during normal operation [1]. The debonding defect as the main defect type of C/E FAHS affects the material performance seriously. Therefore, it is of great significance to find an effective nondestructive testing (NDT) technique to detect the debonding defects of C/E FAHS.

At present, several NDT techniques are used in the aerospace domain to detect debonding defects of aluminum honeycomb structure [2]: holographic interferometry, ultrasonic and infrared thermography.

Holographic interferometry (HI) is a whole-field optical method that allows non-contact measurement of surface displacement in the micron to sub-micron range. Because of its high sensitivity, surface, subsurface and interior details of the object can be obtained [3,4]. Binu et al. [5] proposed a defect identification strategy of HI through square wave excitation. This method enhanced the speed and accuracy of inspecting the debonded sandwich structures. Much research has utilized Lamb wave propagation, using the leaky lamb wave method for sandwich structures [6]. Chong et al.[7] presented a full-field ultrasonic guided wave method to inspect a composite sandwich specimen. He used continuous wavelet transform based on fast Fourier transform as a single-frequency band pass filter to filter the full-field ultrasonic data in the 3-D space-time domain at the selected dominant frequency. However, ultrasonic method has a lower detection efficiency. Lu et al. [8] proposed the immersion C scan method to detect debonding defects of honeycomb sandwich structures. The results depict that C scan imaging can provide a digital non-destructive testing method for honeycomb sandwich structure. However, immersion C scan is a contact detection method and need water as the coupling agent, and these factors affect the applicability of this method and the detection results.

Infrared thermography [9–12] based on photothermal radiometry effect presents some advantages over above techniques: it is less time consuming, less expensive, portable and subsurface defect location can be detected [13]. Clemente et al. [14] discussed Lock-in thermography (LIT) and Pulsed thermography (PT) in relation to the NDT of CFRP facings-aluminum honeycomb sandwich structures. The experimental results illustrated LIT phasegrams produce higher SNR than PT, and PT is affected by different problems (no-uniform heating, emissivity

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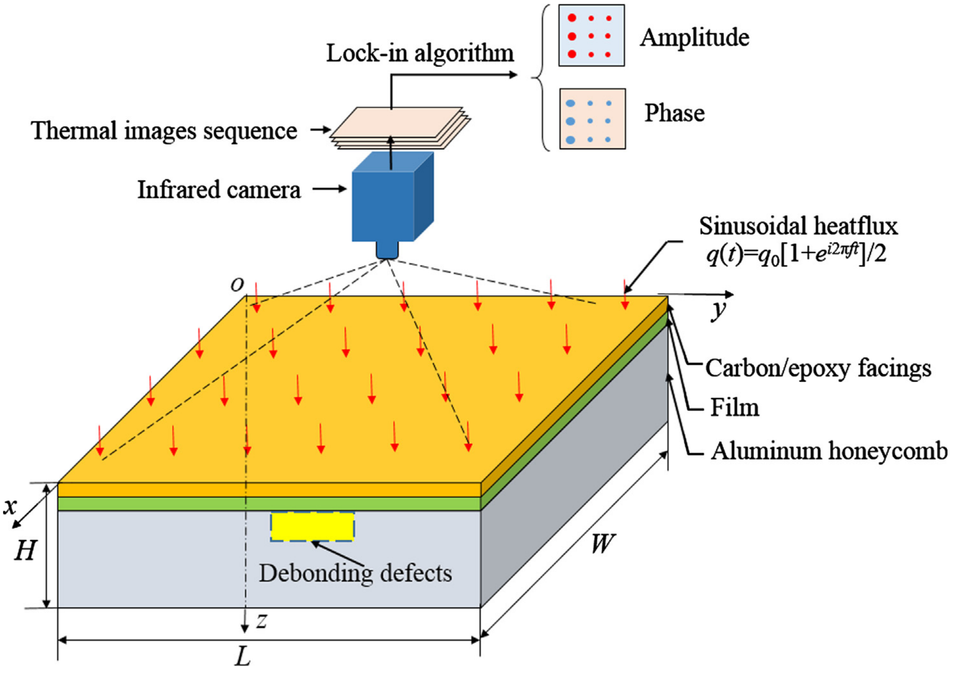

Fig. 1. Three-dimensional heat conduction model C/E FAHS by LIT.

variations, environmental reflections and surface geometry). Therefore, the debonding defects of C/E FAHS are detected using LIT in the present study.

The aim of this paper is to detect C/E FAHS debonding defects by LIT with the higher signal to noise ratio (SNR). To accomplish this aim, this paper is organized as follows, in Section 2, a mathematic model based on three dimensional (3D) heat conduction equation is employed for describing the thermal diffusion behavior of C/E FAHS when exposed to a periodic modulated excitation heat flux; Section 3 highlights the FEM simulation and the influence of the mean parameters (light power intensity, modulation frequency, number of excitation cycles), and these parameters are important for the NDT&E of C/E FAHS; Section 4 introduces the experimental study on C/E FAHS; The conclusions are then presented in Section 6.

2. Mathematical model

The 3D thermal wave model was proposed and used to predict the heat transfer process during LIT inspection. Fig. 1 shows the 3D heat conduction model of C/E FAHS by LIT. The material of C/E FAHS contains three layers, and three layers are carbon/epoxy facings, film and aluminum honeycomb, respectively. The debonding defects often occur between film and aluminum honeycomb. The carbon/epoxy facings were exposed by a periodic modulated excitation heat flux and starting from a given initial uniform temperature T_0. The surface temperature was recorded by an infrared camera and the thermal image sequence can be generated subsequently. Then through lock-in algorithm between the *ac* oscillation component of surface temperature (thermal-wave) and excitation heat flux signal (reference signal), the frequency-domain characteristic parameters (amplitude and phase) images can be obtained.

The C/E FAHS specimen was stimulated by an external sinusoidal excitation signal, and the excitation signal was given by

$$q(t)=\frac{q_0}{2}(1+\sin(2\pi ft)) \tag{1}$$

Here, q_0 is the peak value of heat flux, and f is the sine-modulated frequency.

It can be seen from Eq. (1), the excitation heat flux signal consists of *ac* oscillation component ($q_0/2\times\sin(2\pi ft)$) and *dc* component ($q_0/2$). Therefore, the radiation signal T also contains the *ac* component T_{ac} (so called thermal-wave) and *dc* component T_{dc} (thermal trend items). T_{dc} can reduce the detection SNR, for this reason, T_{dc} should be removed. Assuming that every layer of C/E FAHS is an isotropic material, and the mathematical functions of 3D heat conduction in C/E FAHS are shown as Eq. (2),

$$\frac{\partial^2 T_i(x,y,z,t)}{\partial x^2}+\frac{\partial^2 T_i(x,y,z,t)}{\partial y^2}+\frac{\partial^2 T_i(x,y,z,t)}{\partial z^2}=\frac{\rho_i c_i}{k_i}\frac{\partial T_i(x,y,z,t)}{\partial t}\quad i=1,2,3 \tag{2a}$$

$$\frac{\partial^2 T_{dci}(x,y,z,t)}{\partial x^2}+\frac{\partial^2 T_{dci}(x,y,z,t)}{\partial y^2}+\frac{\partial^2 T_{dci}(x,y,z,t)}{\partial z^2}=\frac{\rho_i c_i}{k_i}\frac{\partial T_{dci}(x,y,z,t)}{\partial t}\quad i=1,2,3 \tag{2b}$$

Here, i represents different layer. c_i, ρ_i, k_i is the specific heat capacity, the density and thermal conductivity of different layer material, respectively.

Only the heated surface has the convection heat transfer and radiation heat transfer, and assume other surfaces are heat insulate. The initial condition and the boundary conditions are as follows,

the initial condition:

$$T_i(x,y,z,t)|_{t=0}=T_{dci}(x,y,z,t)|_{t=0}=T_{\mathrm{am}} \tag{3}$$

where T_{am} is the ambient temperature.

The boundary condition:

$$-k_1\frac{\partial T_{dc}(x,y,z,t)}{\partial z}\bigg|_{z=0}=\frac{q_0}{2}+h[T_{\mathrm{am}}-T_{dc}(x,y,0,t)]+\varepsilon\sigma[T_{am}^4-T_{dc}(x,y,0,t)^4] \tag{4a}$$

$$-k_1\frac{\partial T_1(x,y,z,t)}{\partial z}\bigg|_{z=0}=-k_3\frac{\partial T_3(x,y,z,t)}{\partial z}\bigg|_{z=(L_1+L_2+L_3)}=0 \tag{4b}$$

$$\frac{\partial T_{dc}(x,y,z,t)}{\partial z}\bigg|_{z=0}=\frac{\partial T_{dc}(x,y,z,t)}{\partial z}\bigg|_{z=L_1}=\frac{\partial T_{dc}(x,y,z,t)}{\partial z}\bigg|_{z=L_1+L_2}=\frac{\partial T_{dc}(x,y,z,t)}{\partial z}\bigg|_{z=L_1+L_2+L_3}=0 \tag{4c}$$