

EXPERIMENTAL STUDY ON DEFECTS DETECTION IN GFRP LAMINATES USING LOCK-IN INFRARED THERMOGRAPHY TECHNOLOGY

by

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To detect the debonding defect of glass fiber reinforced polymer laminate, the lock-in infrared thermography non-destructive testing system is built and the systematic testing research are conducted, and the effect of different geometrical parameters of debonding defects on the testing results are analyzed. Algorithms such as inter frame differential-multi frame cumulative average method, polynomial fitting-correlation coefficient method, and time-difference contrast method are used to process the image sequence, and signal-to-noise ratio and information entropy are defined as the parameters for evaluating the performance of algorithms.

Key words: Glass fiber reinforced polymer laminate, infrared thermography, image sequence, signal-to-noise ratio, information entropy

Introduction

GFRP as one of the common combined materials, has the advantages of light weight, corrosion preventive, good chemical stability, etc. So, it is used in many industrial fields, including but not limited to construction, transportation, aerospace, energy and other fields [1]. However, in the production and use of GFRP laminates, due to the existence of various factors, which ultimately lead to fiber-reinforced composite products are prone to debonding defects, and a major safety hazard is caused [2]. Therefore, in order to find the internal defects of GFRP laminates in time, ensure the integrity of its structure, it is necessary to conduct non-destructive testing of GFRP laminates.

Based on the principle of infrared radiation, infrared thermal imaging non-destructive testing [3,4] is a non-destructive testing method developed in recent years. And it is characterized by fast testing speed, non-contact, non-pollution, and sensitivity to near-surface defects and features of components [5,6].

Infrared thermal imaging test

Principle of detection

Figure. 1 shows the diagrammatic sketch of the testing system, which mainly includes the thermal excitation system, the image acquisition system, the image analysis and processing system.

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The principle is that the heat transformation causes a temperature change on the surface of the specimen, and the infrared camera collects the temperature signal and transmits it to a computer.

When the lock-in thermal excitation is applied to the specimen, the heat flow on the specimen surface is shown as follows:

$$q(t) = \frac{q_0}{2}(1 + \sin(2\pi ft)), \quad t \in [0, T] \quad (1)$$

where $q(t)$ is the heat flow from halogen lamps, q_0 is the maximum heat flow output from halogen lamps, f is the phase-locked frequency, and T is scan period of the modulation signal.

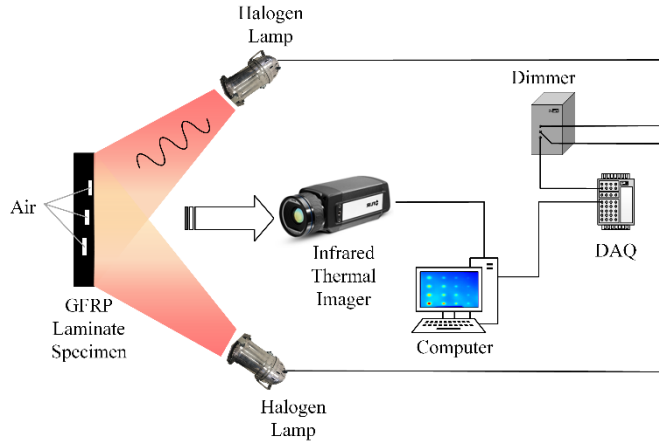


Figure 1. Testing system

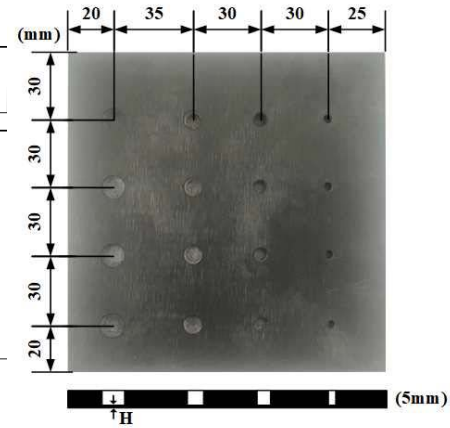


Figure 2. Practicality

picture of GFRP laminate

Specimen preparation

GFRP laminate with dimensions of 140mm×140mm×5mm was prepared and its debonding defects were simulated by drilling blind holes. Figure 2 is a practicality picture of GFRP laminate.

Testing parameters

The power of the halogen lamp was set to 2000 W, the lock-in frequency was 0.05 Hz. The sampling rate of the infrared thermal imager was 20 Hz and the acquisition time is 40 seconds to acquire the surface temperature of GFRP laminate.

Testing results and analysis

Effect of geometrical parameters of defects on surface temperature difference

Figure. 4 shows the effect of different defect depths and defect diameters on the surface temperature difference of the specimen.

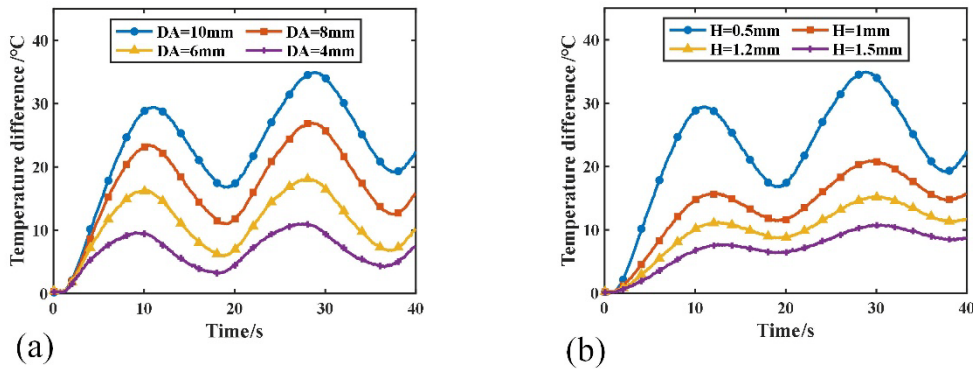


Figure 4. Temperature difference of surface;

a)different defect diameters and (b) different defect depths

As shown in fig. 4 (a), for defects with the same diameter, the temperature difference between the presence and absence of defects will gradually increase over time, and the shallower the defect depths, the more significant the temperature difference. According to fig. 4 (b), it appears that when the depths of the defect are the same, the larger the defect diameters, the more obvious the temperature difference.

Image sequence processing

Processing algorithms

Inter frame differential-multi frame cumulative average method

Inter frame differential method is to obtain the outline of defects by performing a differential operation on two adjacent frames in an infrared thermal image sequence[7]. The original image sequence is $\{I_1(a,b), \dots, I_{x-1}(a,b), I_x(a,b)\}$, The new image sequence obtained by sequentially performing first-order differencing on each frame according to eq. (3) is $\{P_1(a,b), P_2(a,b), \dots, P_{x-1}(a,b)\}$.

$$P_{x-1}(a,b) = I_x(a,b) - I_{x-1}(a,b) \quad (2)$$

where (a,b) is pixel position coordinates, and x is the number of frames corresponding to the current image.

The residual images containing target defects and random noise are obtained after the image sequence is processed by inter frame differencing [8]. It is calculated as shown in eq. (4).

$$\overline{P_i(a,b)} = \frac{1}{k} \sum_{i=1}^k P_i(a,b) \quad , \quad k \leq x-1 \quad (3)$$

where $P_i(a,b)$ is the i^{th} frame image in the new image sequence obtained by inter-frame difference processing, and k is the number of images processed by the cumulative average.

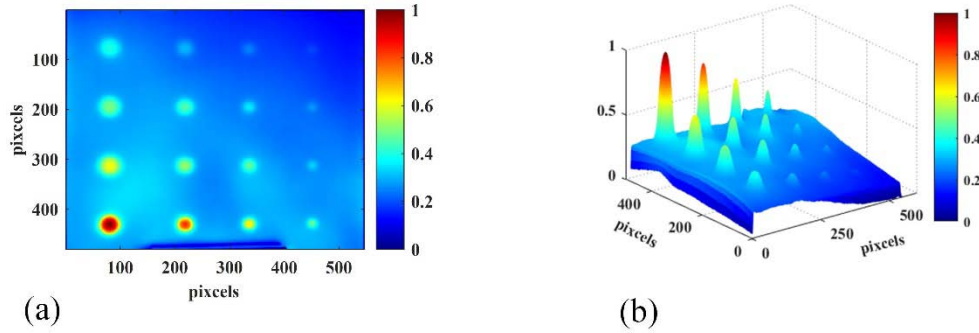


Figure 5. Results of FD-MCA; (a) 2-D graph and (b) 3-D graph

Figure. 5 shows the processed image. According to fig. 5, the size, position and contour of defects in the image can be clearly identified, and the contrast between areas with and without defects is obvious, with little noise interference.

Polynomial fitting-correlation coefficient method

The polynomial fitting-correlation coefficient method (FCC) is to construct a set of the dataset based on the temperature value T_n corresponds to every pixel (x,y) in the image sequence at time t_n . The polynomial model in the form of eq. (5) is used to perform curve fitting according to the least square method. The fitting image sequence can be obtained according to the fitting coefficient and time series[9].

$$T(t) = \sum_{n=0}^N a_n t_n \quad (4)$$

where a_n is the fitting coefficient.

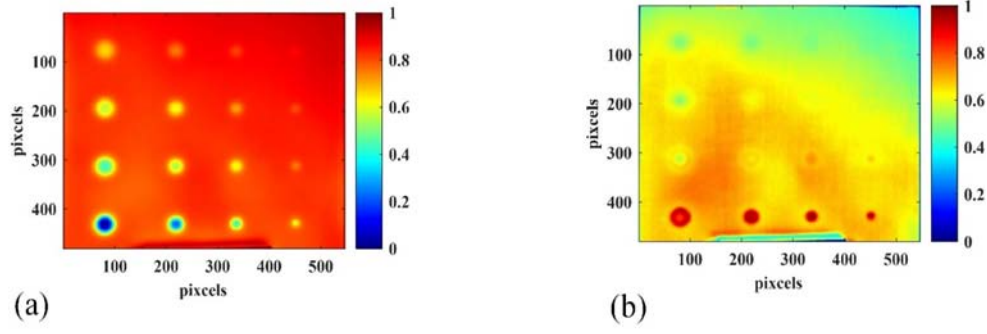


Figure 6. Results of FCC; (a) the coefficients of the second-order coefficient and (b) the coefficients of the constant coefficient

The original thermal image sequence was processed by FCC. It can be seen from fig. 6 that there are more defects shown in the second-order coefficient diagram and the outline of defects is clear. However, there are many noise points in the constant coefficient diagram.

Time-difference contrast method

The time difference contrast method (TDC) can subtract the two frames produced at different times[10]. The two frames can be associated by a multiplicative scale factor α . There is

$$I_1 = \alpha I_2 \quad (5)$$

where I_1 and I_2 are the images at moments t_1 and t_2 , respectively.

The two images are differentially processed. There is

$$I_d = \alpha I_2 - I_1 \quad (6)$$

where I_d is differential image.

The image processed by the time difference comparison method is shown in fig. 7. According to the figure, we can find that although all defects can be identified, there is still a quantity of noise in the processed image.

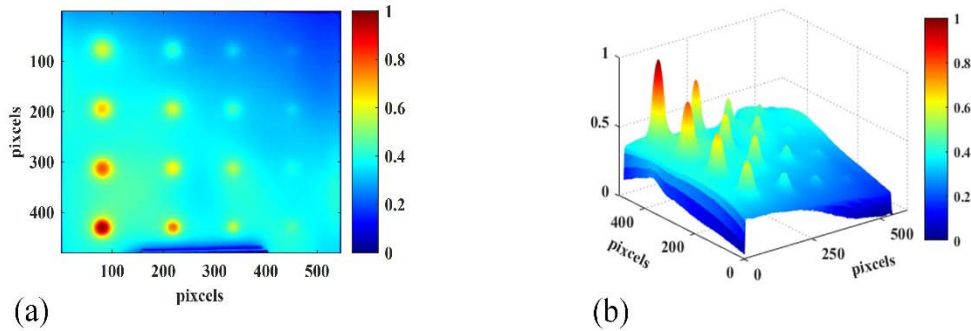


Figure 7. Results of TDC; (a) 2-D graph and (b) 3-D graph

Evaluation of algorithms

For comparing the effect of the above-mentioned image sequence processing algorithms, this paper uses signal-to-noise ratio (SNR) and the information entropy (IE) to evaluate the best result of each algorithm.

The higher the SNR is, the less noise in the image is. The SNR reads as

$$SNR = \frac{|E_d - E_{nd}|}{\sigma_{nd}} \quad (7)$$

where E_d is mean pixel value of the defective areas, E_{nd} is mean value of pixel value in the defect free areas, and σ_{nd} represents standard deviation of defect free areas.

The higher the information entropy, the richer the details of the defect features contained in the image [11]. The information entropy can be expressed by

$$IE = -\sum_{i=1}^N (E_i(x, y) \log_2 E_i(x, y)) \quad (8)$$

where $E_i(x, y)$ and $\log_2 E_i(x, y)$ represents frequency of occurrence of the corresponding gray value at a pixel point in the image in the whole image, and the logarithm of the frequency of occurrence of the corresponding gray value at a point.

The SNR and IE of the images processed by the above-mentioned algorithms are computed and fig. 8 (b) shows the outcomes. It can be found in the figure that the IE of the images processed by the three algorithms TDC, FCC and FD-MCA are higher than that of the original thermal image. And the SNR of the image processed by FCC and FD-MCA is significantly higher than that of the original image, indicating that the FCC and FD-MCA algorithms have a stronger ability to suppress noise.

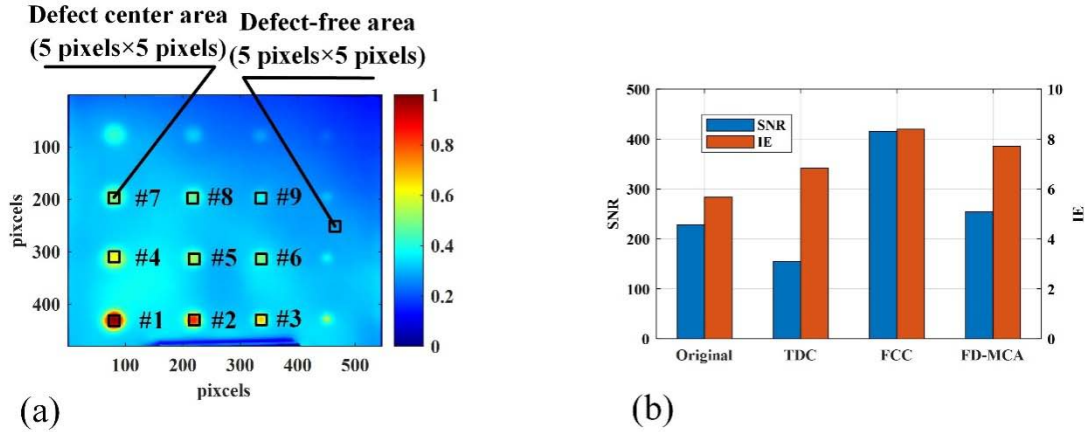


Figure 8. SNR reference area and calculation of SNR and IE

Conclusion

For detecting debonding defects in GFRP laminates, a lock-in thermography inspection system was built, and the effect laws of diameters and depths of defects on surface temperature difference were discussed. FD-MCA, FCC and TDC were used to process the original image sequences, and the results show that FD-MCA, FCC and TDC can improve the image quality, and the FCC algorithm has a stronger ability to suppress the noise, which can be more effective in the extraction of defect information.

Acknowledgments

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Nomenclature

t -scan period of the modulation signal, [s]
 $q(t)$ - heat flow from halogen lamps, [W/m²]
 f - phase-locked frequency, [Hz]

x, y -coordinates spaces, [m]
 q_0 - maximum heat flow, [W/m²]
SNR - signal to noise ratio, [db]

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