Shearography With Thermal Loading For Defect Detection Of Small Defects In Cfrp Composites

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SHEAROGRAPHY WITH THERMAL LOADING FOR DEFECT DETECTION OF SMALL DEFECTS IN CFRP COMPOSITES

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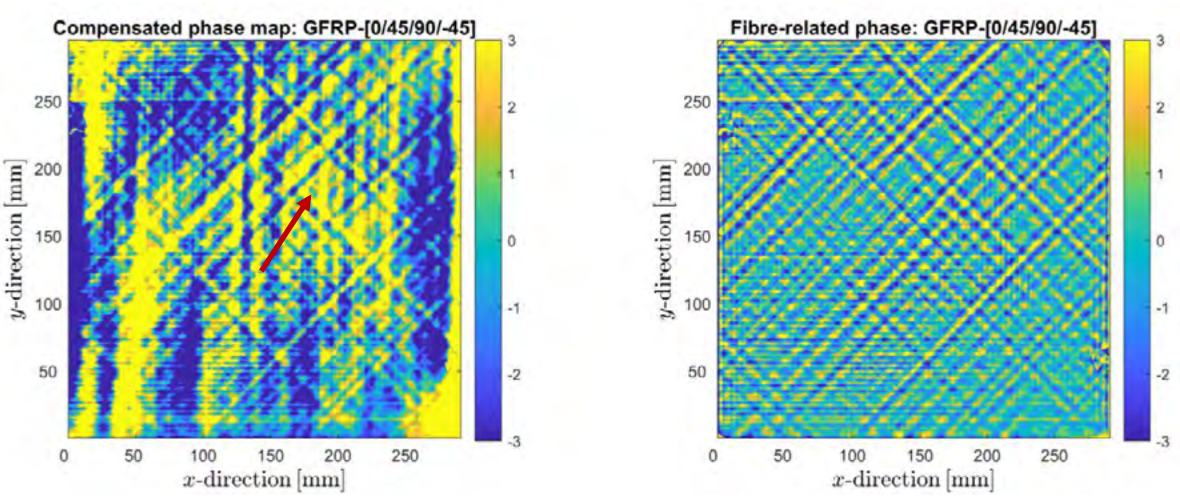
Abstract
Composite materials, e.g., carbon fibre-reinforced polymers (CFRPs), have been increasingly adopted in safety-critical structures across different industries. However, various defects including delaminations and fibre breakage can occur in the composite structures that may endanger the whole structure severely. Therefore non-destructive testing (NDT) of composites is critical to ensure structural integrity and safety. It is important to advance the capabilities of NDT of composite materials towards early-stage damage, e.g., small defects of millimetre scale, to avoid future failure. The objective of this work is to study the detection of small defects in CFRP laminates using shearography with thermal loading. In this paper, a thermal-mechanical FEM model was established in Abaqus to assist shearography inspection of the composite laminate. This FEM assistance is capable of evaluating different thermal loading schemes for defect detection. A rational selection of the reference and signal interferograms from the heating/cooling sequence is determined for reliable defect detection. We will present both experimental and numerical results on the detection of small defects in CFRP.

1. Introduction

Carbon fibre-reinforced polymers (CFRPs) are being increasingly adopted in safety-critical structures in the aerospace, marine and wind energy sectors [1–3]. Different types of defects and damage, e.g., delaminations, fibre breakage and impact damage can occur in composite structures. Non-destructive testing (NDT) of these composites is therefore critical to ensure structural integrity and safety [1,2]. A key demand for NDT is to detect the presence of early-stage defects and damage to avoid future failure. Hence, it is important to advance the capabilities of NDT of composite materials towards small defects, e.g., in millimetre size. Among different NDT techniques, digital shearography is a non-contact and full-field optical method that has received considerable interest in various industries, particularly, for the inspection of aerospace and marine composite structures [1,4–7]. Shearography NDT methods [4,8,9] can offer effective solutions for the detection of both manufacturing and in-service defects in composites. However, their efficacy in detecting small defects is not fully characterised yet [10].

The objective of this work is to study the detection of small defects in CFRP composite laminates using shearography with thermal loading. Shearograhy reveals defects by comparing reference and signal interferograms of the test specimen under loadings. One of the major issues of shearography with thermal loading is in fibre-related deformation, which arises from the difference in thermal conductivity and thermal expansion coefficient between fibre and resin. This fibre-related deformation can affect significantly the efficacy of defect detection (Figure. 1). Fibre-induced deformation in shearography with thermal loading depends on the moments (i.e., reference and signal states) during heating/cooling. So a rational selection of the reference and signal interferograms from the heating/cooling sequence is needed. In this study, a thermal-mechanical FEM model was established in Abaqus to assist shearography inspection. This FEM assistance is capable of evaluating different thermal loading schemes for defect detection.

The paper is organized as follows. In section 2, we introduce a CFRP specimen and the shearography setup. A set of flat bottom holes were drilled from the back surface of the CFRP specimen to indicate defects in composites. In section 3, we present modelling and experimental results of defect detection in this CFRP specimen. The conclusions are given in section 4.



(a) (b)

Figure 1. (a) Shearography result of a marine GFRP laminate (size of 300×300×51 mm^3 and layup of [0/45/90/-45]) with a defect at 25 mm depth (marked in red area). Fibre-related deformation noise affects the detection of defects in the composite severely. (b) Fibre-related deformation noise extracted by using 2D FFT. The fibre-related deformation reflects the layup of the composite.

2. CFRP specimen and shearography system

2.1. CFRP specimen with flat bottom holes

Figure 2(a) shows the geometry of the specimen. The specimen is a crossply ($[0/90]_{10s}$) CFRP specimen with a size of 200×200×4 mm^3, which was made from CYCOM 977-2 by Cytec. It is a representative test specimen for aerospace composites. A set of flat bottom holes (FBHs) was milled from the reverse side of the specimen. The diameter and the remaining thickness of the holes are 0.4-3 mm and 1-3 mm, respectively, indicating small defects in the CFRP composite laminate.

For modelling part, considering the complexity of the FEM model due to the presence of FBHs of various diameters and depths, it is challenging to model all the reference defects in the composite laminate in Abaqus. Therefore only the defects of the first column (defect diameters of 0.4 to 3 mm at 3 mm depth; the hole depth corresponding to the remaining thickness of 1 mm) were modelled in order to simplify the model. The established model in Abaqus is shown in Figure 2(b). The local part of FBHs is shown in Figure 2(c).

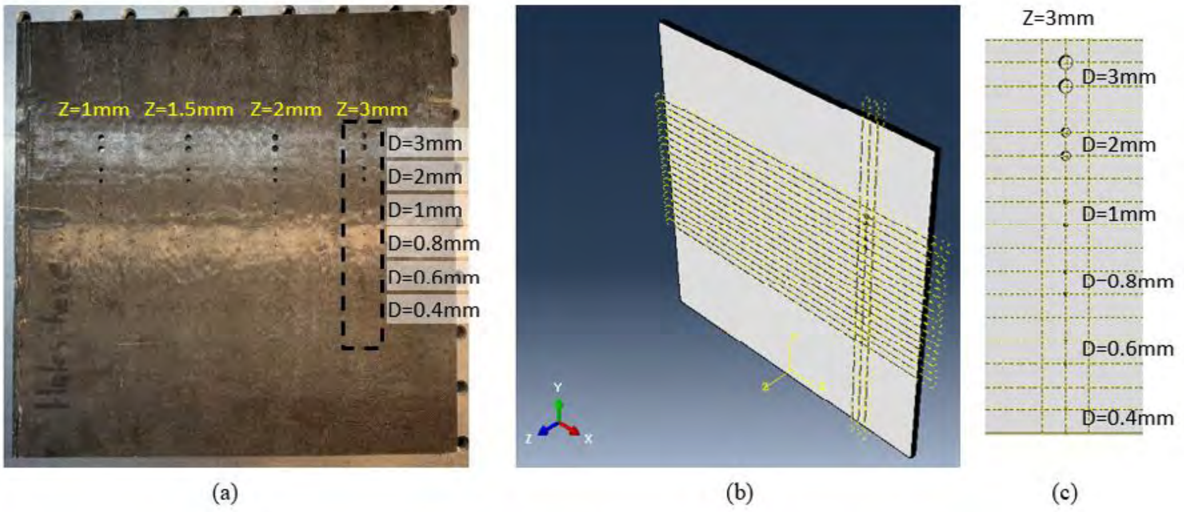


Figure 2. (a) The test CFRP with flat bottom holes as reference defects (back surface, the defects marked in the black rectangle area were modelled in Abaqus), (b) the FEM model established in Abaqus, (c) local part of the FBHs (diameters of 0.4-3 mm at 3 mm depth)

2.2. Shearography System

The schematic of the out-of-plane shearography system is shown in Figure 3. A laser beam of 532 nm wavelength was expanded to illuminate the specimen surface (defect-free side), creating a speckle pattern. By using a shearing device, the scattered laser light from two neighboring points on the surface of the specimen can meet together in the camera, forming a speckle interferogram. The shearing device enables temporal phase-shifting to obtain the phase of the recorded speckle images.

The specimen was heated by three halogen lamps of electrical power of 0-1000 watts each. The transient temperature on the specimen surface was monitored with a thermal IR camera during the inspection. The specimen was heated for approximately 5 minutes in a cyclic heating mode (10 cycles in total), resulting in a temperature rise of 40 °C on the front. Each heating cycle included 30 s of heating with the lamps on and 5-6 s with the lamps off to capture the sets of phase-shifted speckle interferograms. During the cooling, the sets of phase-shifted speckle interferograms were continuously captured. All sets of interferograms were processed to obtain shearography phase map sequence with respect to time. The shear distance is around 3.2 mm in the *x*-direction (horizontal). Compensated phase maps were calculated for defect detection, as in [6,7].

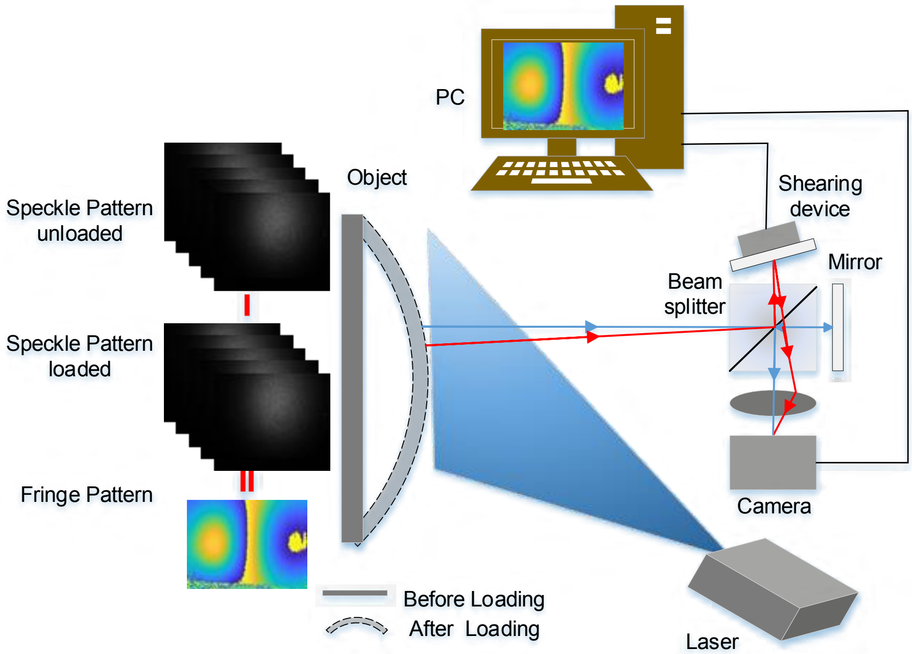


Figure 3. Schematic of out-of-plane shearography setup

3. Results

This section presents experimental and numerical results on the detection of small defects in CFRP. For this CFRP specimen of 4 mm thick with [0/90] layup, FEM preliminary (Figure. 4(a)) predicts the detection of defects with diameters of 0.6-0.8 to 3 mm at 3 mm depth. However, the realistic phase maps in Figure. 4(b-c) contain high fibre-related deformation which reflects the layup of the material and not the defects.

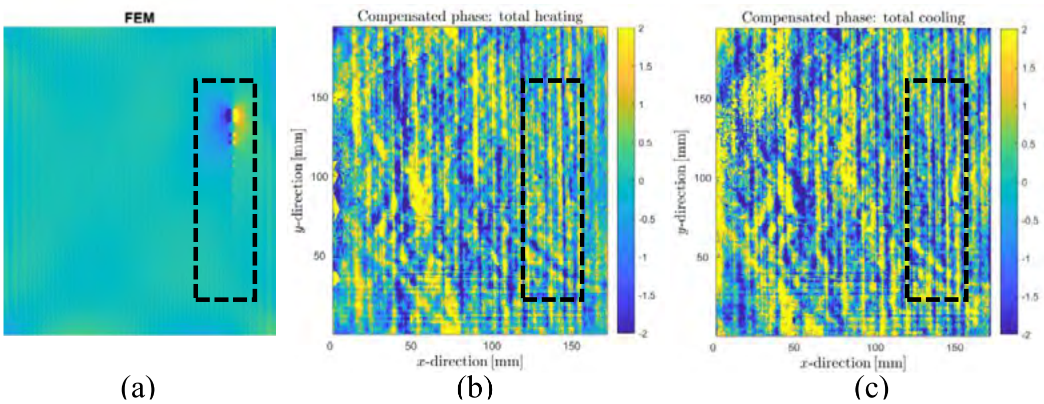


Figure 4. Comparison of phase maps: (a) FEM preliminary prediction, (b) only during heating, (c) only during cooling. The defects in the black rectangle area were modelled for comparison.

Fibre-induced deformation in shearography with thermal loading depends on the moments during the heating/cooling scenario when the so-called reference and signal interferograms are captured. Figure. 4 (b,c) represents the worst cases with the deformation during heating or cooling which satisfy the initial definition of one before and another after the object is slightly deformed [11,12], however, they are not useful as the fibre-induced deformation is higher than the expected signal from defects. At the same time, successful detection of defects in the same specimen during the same test (Figure. 5) is possible. For this, a rational selection of the reference and signal interferograms from the heating/cooling sequence is determined for reliable defect detection. The corresponding shearography pair approach has been developed through the analysis of fibre-induced and defect deformations during heating and cooling, where optimal shearography pairs (i.e. the reference and signal interferograms) were determined for reliable defect detection. The results show that those pairs exist at the moments when the temperature of the front surface of the specimen during heating is close to the same value during cooling.

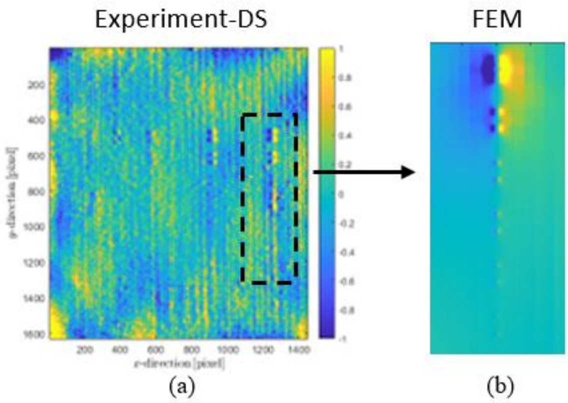


Figure 5. Successful detection of defects in the same specimen during the same test by a rational selection of the reference and signal interferograms: (a) experimental result, (b) FEM result.

4. Conclusions

In this work, we present recent experimental and numerical results on the detection of small defects in CFRP laminate. By rational selection of time moments for so-called reference and signal interferograms with respect to the heating scenario, the effect of fibre-induced deformation in composite materials can be minimized. The experimental and numerical results indicate that this approach enables the detection of millimetre- and submillimeter defects in CFRP. These detection results are one of the smallest defects detected with shearography and reported in the literature.

Acknowledgments

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