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Spatially modulated thermal excitations for shearography non-destructive inspection of thick composites

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ABSTRACT

With the increasing application of thick composites in marine, wind energy and aerospace industries, the inspection of thick composites becomes more and more challenging when considering the variety of thick structures (e.g., laminate, sandwich, honeycomb structures). Shearography is a full-field and non-contact optical non-destructive testing (NDT) method which is normally used to inspect composite laminates up to 10 mm while for the thick composite laminates (e.g., with the thickness of more than 50 mm), its performance is not clear yet. In shearography NDT, a defect-induced anomaly is revealed from fringe or phase maps obtained by comparing two states of deformation of the specimen to be inspected. Thermal loading is widely used to deform the specimen due to its advantages of convenience for on-site inspection and cost-effectiveness. The objective of this study is to improve the defect detection capabilities of shearography when used to inspect thick composites. For that, spatial modulated thermal excitations are investigated. A thick composite model has been built in Abaqus to assist the shearography inspection. Various kinds of spatially modulated heating including local heating and global heating are explored for thick composite inspection with shearography in order to evaluate the corresponding efficacies in defect detection. We will present both experimental and numerical results on spatial modulated thermal loading. Defect-induced shearographic responses subjected to local and global thermal excitations will be discussed in this paper, including the influence of short-time heating and long-time heating on thick composite inspection. Current results indicate that long-time heating is more favorable when inspecting deep defects in thick composites, and with local heating it is possible to increase the defect-induced signal when compared with global heating.

Keywords: shearography, thick composite inspection, finite-element modelling, spatial modulation

1. INTRODUCTION

Digital shearography (DS) [1-3] has been used for non-destructive inspection of composite materials due to its advantages of full-field and non-contact measurement and its capability of detecting various defects (e.g., delaminations and fibre breakage). Shearography non-destructive testing (NDT) of composite laminates up to 10 mm thickness works well [4-6], however, for thick composite materials (e.g., with thickness of 50 mm and more), which are increasingly used in marine, wind energy and aerospace industries, the efficacy of shearography has not been fully understood.

Shearography reveals defects by comparing two states of deformation of the tested specimen. Therefore, a certain form of loading is necessary to be applied during inspection. The loading methods in shearography include thermal loading, pressure loading, vibration, and so on. Among the various loading methods, thermal loading [6-8] is widely used in shearography to excite the tested object because of its advantages of convenience for on-site inspection and cost-effectiveness.

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The purpose of this study is to evaluate the efficacies of shearography with modulated thermal loading for thick composite inspection. The example test object is a thick composite panel from the marine industry. We have applied finite-element modelling (FEM) [6][8] for predicting the thermal-mechanical response during inspection. Two kinds of modulated heating including local heating (LH) and global heating (GH) are investigated in order to improve the defect detection capability of shearography when used to inspect deep defects (e.g., defects at more than 20 mm depth) in thick composites. In this paper, we present FEM-assisted shearography to investigate defect detection capabilities of a thick glass fiber reinforced polymer (GFRP) laminate with a deep defect. A flat bottom hole [8-9] is used to indicate major defect in thick composite. In section 2, we describe the tested GFRP panel and the experimental setup. In section 3, we present the comparison of modelling and experimental results of the GFRP panel subjected to global heating. We also present defect-induced shearographic responses subjected to local and global thermal excitations, both short-time heating and long-time heating have been investigated in section 3. Conclusions are given in section 4.

2. EXPERIMENTAL AND MODELLING SETUP

Figure 1(a) and 1(b) shows the geometry of the thick composite specimen. The specimen (300×300 mm^2) is a monolithic ($[0/+45/90/-45]_{60}$) GFRP panel with a total thickness of 51 mm. It is a representative test specimen for composite ship construction. A flat bottom hole is milled from back side. The diameter and the remaining thickness of the hole are 60 mm and 25 mm, respectively, indicating major defect at 25 mm depth in the thick composite specimen.

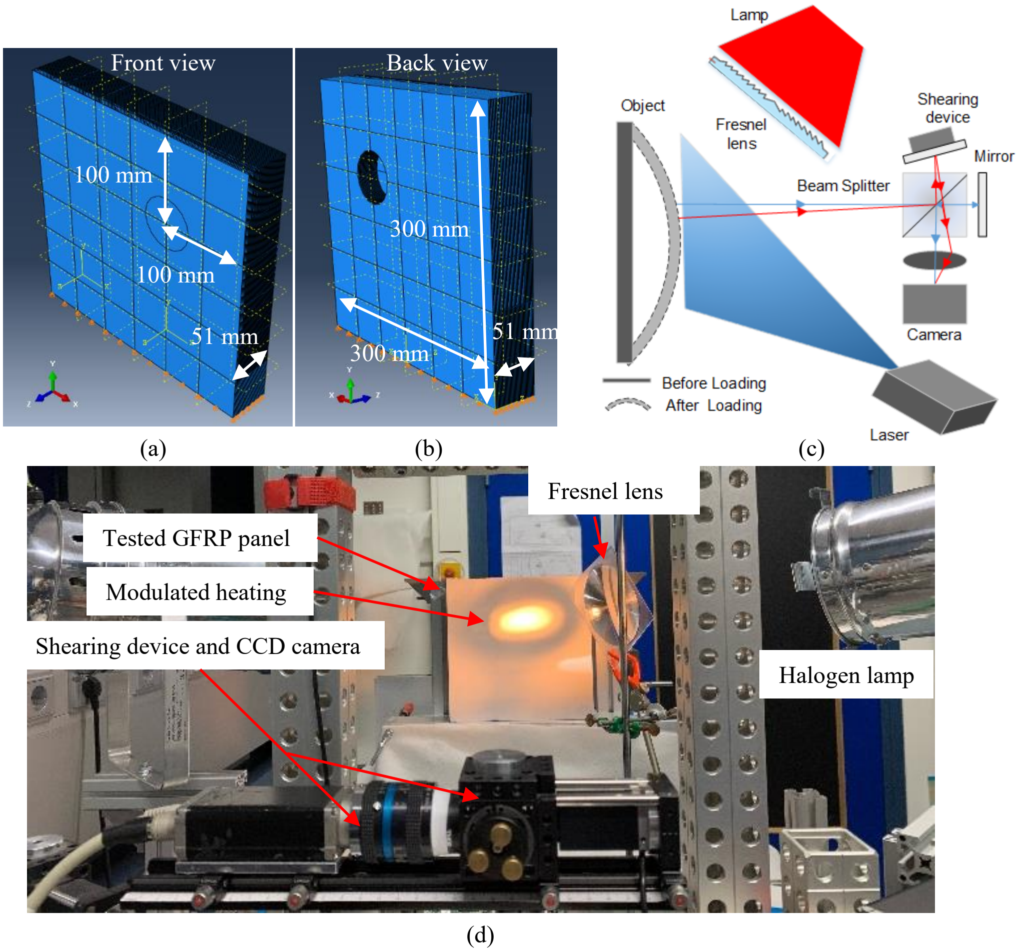

Figure 1 Schematic of the GFRP panel with flat bottom hole used in the experiment: (a) Front view. (b) Back view. (c) Schematic of the out-of-plane shearography setup. (d) Shearography instrument with modulated heating

The schematic diagram of an out-of-plane shearography system is shown in Figure 1(c) and the shearography instrument in the lab is shown in Figure 1(d). A laser beam with the wavelength of 532 nm is expanded to illuminate the surface of the specimen, creating a speckle pattern. By using a shearing device, the scattered laser light from two neighboring points on the specimen surface can meet together in the charged coupled device (CCD) camera, forming a speckle interferogram. The shearing device enables temporal phase-shifting for obtaining the phase of the recorded speckle interferograms. The shear distance is around 7 mm. The specimen is positioned in focus at about 0.9 m from the CCD camera. The specimen is heating by a 0-1000 Watt halogen lamp with the intensity modulation. Transient temperature was measured with a FLIR A65 thermal infrared (IR) camera. It was given as an Abaqus input for characterizing heat flux distribution on the surface of the specimen. A Fresnel lens is used to modulate the distribution of the light from the halogen lamp. In this way, the heat on the object surface can be spatially modulated.

3. RESULTS AND DISCUSSIONS

3.1 Comparison between simulations and experiments of the GFRP panel subjected to global heating

In this section, we compared the numerical results and experimental results of the GFRP panel subjected to global heating. The GFRP panel is described in section 2. Equivalent thermal and mechanical properties [10] are calculated for modelling in order to simplify the FEM model and reduce the computational time. The specimen is freestanding on the optical table during inspection, in order to achieve this boundary condition in the model, the displacement of the bottom surface along y-direction is constrained (UY = 0) as seen in Figure 1(a) and 1(b).

Figures 2(a) and (b) show the transient temperature fields measured by the IR camera and those predicted by FEM after 180s heating. The initial temperature of the specimen (before heating) is around 20 ℃. Their corresponding difference is shown in Figure 2(c). The overall difference is -0.4 ℃ to 0.4 ℃, which shows a good agreement between simulations and experiments. The comparison of fringe maps obtained by shearography and simulated by FEM is shown in Figures 2(d) and 2(e), the maximum phase difference is around 2π rad (~one fringe) as shown in Figure 2(f).

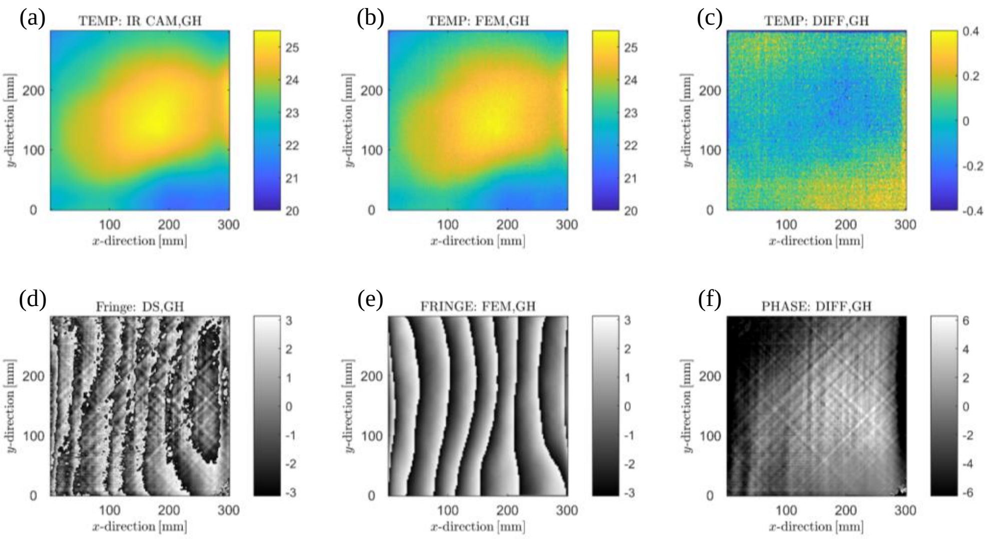

Figure 2 Comparison of simulations and experimetnts after 180s heating. (a)-(c): Temperature measured with IR camera and those predicted by FEM and their difference (t = 180s), respectively. (d)-(f): Experimental fringe map, simulated fringe map, and their difference in phase, respectively.

These comparisons indicate that the simulations have reasonable accuracy compared with shearography measurements, therefore, the FEM model can be used to predict thermal-mechanical response to assist shearography NDT.

3.2 Defect-induced shearography responses due to local and global thermal excitations

In this section we present defect-induced shearographic responses of the thick GFRP laminate with the defect subjected to local and global thermal excitations. Both short-time and long-time heating scenarios have been studied in this section. Short-time heating represents the status that the temperature at defect depth has no obvious change, and long-time heating represents the status that the temperature at defect depth has reasonable change. The selection of short-time heating and long-time heating is based on thermal penetration depth. The thermal penetration depth ($\delta_p = 2.3\sqrt{\alpha t}$) is related to thermal diffusivity ($\alpha = 2.27 \times 10^{-7} m^2/s$) of the material and time (t) [11]. The thermal penetration depth of the tested GFRP panel is shown in Figure 3. Since the depth of the artificial defect is 25 mm, a short-time heating scenario is chosen as 180s heating and followed with cooling phase, and a long-time heating scenario is chosen as 5 cycles of 180s heating and 10s cooling, and then followed with cooling phase. Cyclic heating is selected over continuous heating to prevent overheating.

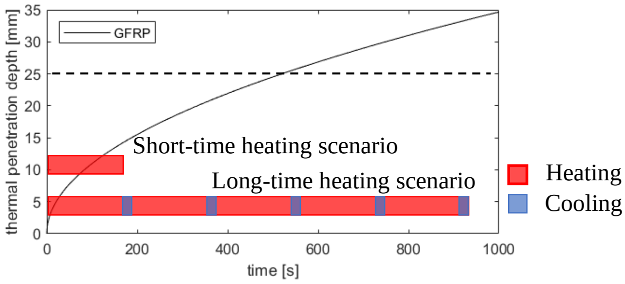

Figure 3 Thermal penetration depth of the tested GFRP laminate

Figure 4 shows the results from short-time heating. Figures 4(a) and 4(b) are fringe maps measured with shearography subjected to local and global heating, respectively. Figures 4(c) and 4(d) are fringe maps predicted by FEM subjected to local and global heating, respectively. The reference deformation status is as before heating and signal deformation status is that during cooling. We can barely see the signature of the defect from the fringe maps in Figure 4. It is because, for short-time heating, the interaction between heat and the defect is limited; therefore the defect-induced deformation change is too small for shearography to detect.

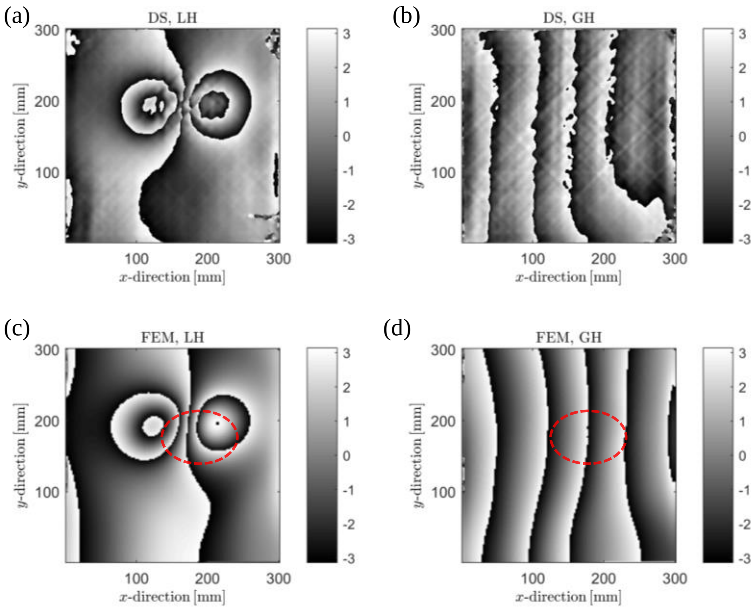

Figure 4 Experimental and numerical results from short-time heating. (a)-(b): Experimental fringe maps by local and global heating, respectively. (c)-(d) Simulated fringe maps by local and global heating, respectively. (the bottom left corner of the defect is marked in red)

Figure 5 shows the results from long-time heating. The reference status is during cyclic heating, and the signal status is that during cooling. The reference status before heating is not favorable since the displacement derivative of the surface increases significantly after heating, which may result in fringe and phase maps with poor quality and make the inspection fail. Therefore, the selections of the reference and the signal status here are related to the quality of the fringe and phase maps, and the efficacy of defect detection.

In Figures 5(a) and 5(b), the presence of the defect is still not visible from fringe maps for both local and global heating. However, for the compensated phase maps (phase maps after removing the global deformation) as shown in Figure 5(c) and 5(d), the signature of the defect is much more obvious. In Figure 5(c), the defect edge of the bottom left corner is clear since it is where the majority of heat is concentrated in. The signature of the defect is more visible in Figure 5(c) than in Figure 5(d), which may indicate that with local heating it is possible to increase the defect-induced signal compared with global heating. Nevertheless, it is shown in experiments that the efficacy of defect detection by local heating highly depends on the positions of heating. Moreover, it is also shown that local heating with concentrated heat usually has a significant influence on fiber deformation near the surface. It will result in fringe distortion and introduce an additional difficulty to defect detection.

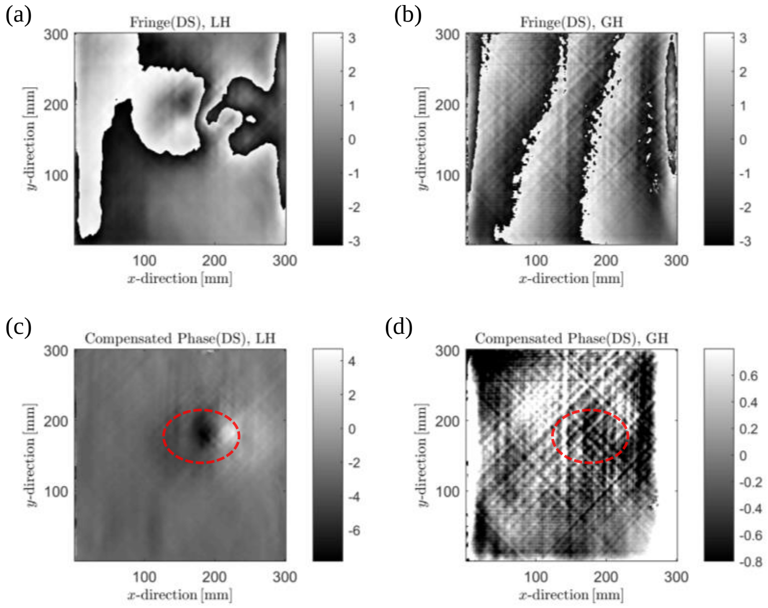

Figure 5 Experimental results from long-time heating. (a)-(b): Experimental fringe maps by local and global heating, respectively. (c)-(d) Compensated phase maps by local and global heating, respectively. (the bottom left corner of the defect is marked in red)

4. CONCLUSIONS

Local and global heating representing spatially modulated thermal excitations have been studied in this paper for the purpose of improving defect detection capabilities of thick composite with shearography. First we have modelled the thermal-mechanical response of a thick GFRP laminate with a single flat bottom hole in Abaqus. The comparison between simulations and experiments shows that the FEM model can be used for predicting the thermal-mechanical response during inspection and therefore can assist shearography NDT. Moreover, defect-induced shearographic responses subjected to local and global thermal excitations, including short-time heating and long-time heating have been investigated. Current results indicate with local heating it is possible to increase the defect-induced signal when compared with global heating, although the efficacy of defect detection by local heating can vary greatly depending on the heating positions. Fiber deformation near the surface and fringe distortion should be treated carefully when applying local heating. More modelling and experimental work regrading boundary conditions, heating positions, defect size and depths are needed in order to draw conclusions that are more reliable.

It is also shown that long-time heating (e.g., heating time more than 10 min) is more favorable when inspecting deep defects in thick composites. Besides, a phase compensation process is necessary to highlight the presence of the deep defect.

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