Shearography and thermography non-destructive testing of composite materials using embedded carbon nanotube (CNT) strips as heaters

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ABSTRACT

The objective of this work is to study defect detection efficacy using embedded carbon nanotube (CNT) fibers as heaters for shearography and thermography. For that, GFRP laminates with various amounts of CNT-doped strips embedded at different layers have been manufactured. Impact tests are performed to create realistic damage in the GFRP specimens for inspection. Shearography and thermography non-destructive testing of the GFRP laminates are performed simultaneously with embedded CNT strips as heating sources before and after the impact test. This research was performed as part of the Horizon Europe COMP-ECO project (grant agreement 101079250). In the future, we aim at developing a novel demonstrator of a composite aerospace structure with integrated CNT-doped sensors that support NDT and enable self-sensing and in-situ SHM capabilities.

Keywords: GFRP, embedded CNT strips, smart structures, shearography, thermography, multi-modal

1. INTRODUCTION

Due to the advantages of lightweight, high specific stiffness and strength, and corrosion resistance, glass fiber-reinforced polymers (GFRP) are extensively used in advanced applications across aerospace, wind energy and marine sectors[1–3]. GFRPs are often used for primary or secondary load-bearing structures where a structural failure can cause catastrophic consequences. Various types of defects such as impact damage, delaminations and fiber breakage can occur in those composite structures that may affect mechanical performance and structural integrity severely[3,4]. Therefore non-destructive testing (NDT) and structural health monitoring (SHM) are important to enhance the safety and maintenance of the structures. Among the different NDT techniques, shearography[5,6] and thermography[7,8] are commonly used for the inspection of composite structures because of their advantages of being non-contact, full-field, and convenient for on-site inspection.

During recent decades, smart composite structures, e.g., carbon nanotubes (CNT) fibers integrated into GFRPs, have gained increasing interest for self-sensing and in-situ SHM capabilities[9,10]. CNTs, due to their characteristics, can improve the electrical and thermal properties of GFRP materials. This allows new possibilities of self-heating (by applying electrical current) for NDT techniques such as shearography and thermography, eliminating the need to use external heat sources such as halogen lamps and air guns.

The objective of this work is to study NDT defect detection efficacies using CNT-doped polyphenylene sulfide (PPS) strips as heating sources. For that, GFRP laminates with different amounts of embedded CNT-doped strips have been manufactured. Impact tests are performed to create realistic damage in the specimens for shearography and thermography inspection. The paper is organized as follows. Section 2 gives the specimen description and experimental methods. Section 3 presents shearography and thermography inspection results. The conclusions are given in Section 4.

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2. SPECIMEN DESCRIPTION AND EXPERIMENTAL METHOD

2.1 Specimen Description

The GFRP laminates were fabricated from HexPly epoxy-glass prepregs (UD1200) and had dimensions of 150 × 100 mm with a layup of [45/0/–45/90]s (8 layers), defined in accordance with ASTM D7136 for impact testing. The GFRP specimens were embedded with three different amounts (4, 6, 8) of PPS/MWCNTs heaters (i.e., CNT strips) that were placed at two different locations (between the 4^{th} and 5^{th} layers, and between the 6^{th} and 7^{th} layers, respectively, with respect to the impact surface). In total there are 6 combinations of manufactured specimens. An example of a GFRP laminate with six embedded CNT strips is shown in Figure 1.

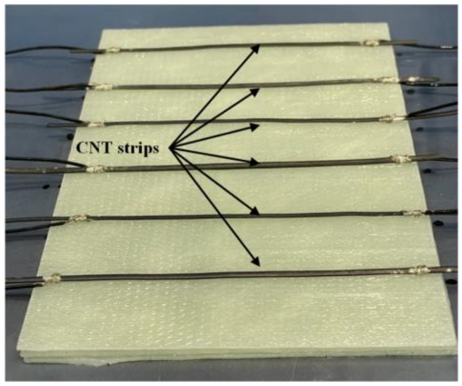

Figure 1. An example of a GFRP laminate with six embedded CNT strips (placed in the middle – between the 4^{th} and 5^{th} layer) illustrating how the CNT strips were implemented into GFRP structure during the manufacturing.

2.2 Shearography and Thermography NDT

Shearography and thermography techniques are well documented, see for example[5–8]. In this study, shearography and thermography NDT of the GFRP laminates are performed simultaneously with CNT fibers as heating sources before and after the impact test. The diagram of the shearography instrument and the IR camera for this investigation is shown in Figure 2. For shearography, an upgraded 3D shape shearography instrument with temporal phase shifting was adapted with the main focus on the out-of-plane deformation[11,12]. 1 pixel of the shearography camera corresponded to around 0.064 mm. The shear distance was around 3.27 mm along the *y*-direction. Four-step phase shifting was used due to its convenience. For thermography, a FLIR A655 infrared camera was used to record the transient temperature of the specimen (1 second per frame). 1 pixel of the infrared camera corresponded to around 0.715 mm.

During the inspection, the GFRP specimen is heated by embedded CNT strips (by applying electrical current) for around 240 s and then naturally cooled for around 780 s, shearography and infrared cameras record data continuously before heating, during heating and after heating, resulting in a total of 265+ sets of phase-shifted speckle interferograms and 1000+ sets of thermograms. All sets of shearography data (phase-shifted speckle interferograms, strain field) are processed through phase filtering and unwrapping, and phase compensation to build phase stacking for defect detection[13,14]. Thermography data (thermal images, temperature field) are processed using algorithms based on principal component analysis (PCA)[15,16].

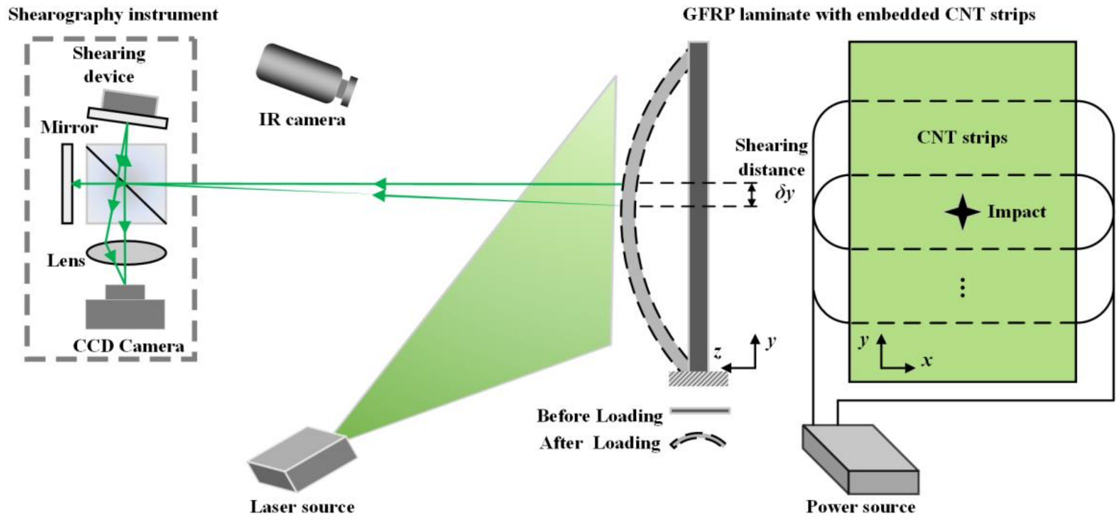

Figure 2. Diagram of the shearography instrument and the IR camera for impact damage detection of the GFRP laminates with embedded CNT strips. The bottom edge of the specimens is clamped during the inspection.

3. RESULTS AND DISCUSSION

3.1 Shearography Inspection Results

The inspection results of the GFRP specimen with 8 CNT strips embedded between layers 4^{th}-5^{th} (with respect to the impacted surface) are presented here as this scenario is expected to provide the most informative detection results in this investigation. Figure 3 shows the shearography results before and after the impact test with energy of around 30 J. The reference phase-shifted speckle interferograms were captured before loading and the signal phase-shifted speckle interferograms were captured after a couple of seconds during the electrical current loading. The embedded eight CNT strips are visible in the phase maps before and after the impact (Figure 3 (a-b)). The impact damage is also detected in Figure 3(b). The presence of the CNT strips serves as background features in the phase map that may affect the defect detection performance. By subtracting the phase maps before and after the impact, the local deformation from the CNT strips can be compensated and a more intuitive phase map highlighting the presence of the impact damage can be obtained for defect detection (Figure 3(c)).

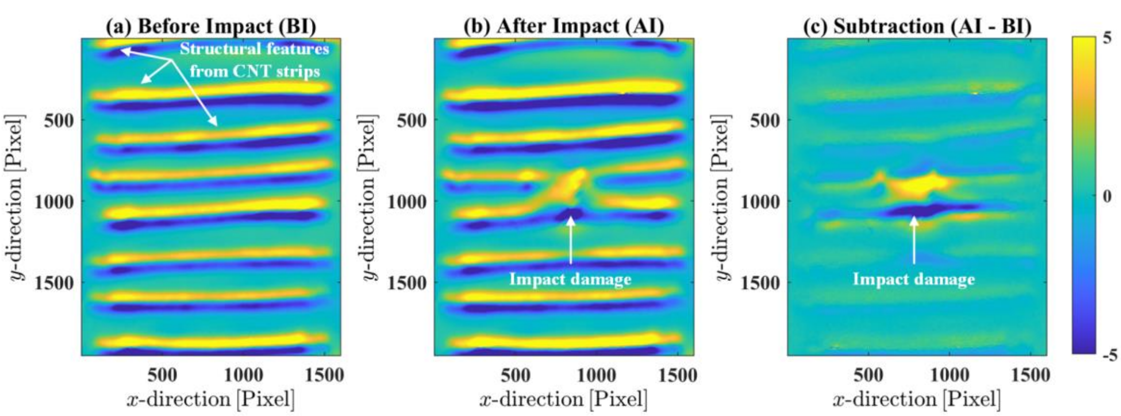

Figure 3. Shearography inspection results on the impacted surface (the out-of-plane surface derivative $\partial w/\partial y$) of the GFRP specimen with 8 CNT strips embedded between layers 4^{th} - 5^{th}. (a) phase map before the impact (baseline), (b) phase map after the impact, and (c) their subtraction that highlights the presence of the damage. Phase units in rad.

3.2 Thermography Inspection Results

The thermography inspection results of the GFRP with 8 CNT strips embedded between the layers 4th-5th (before and after impact) are shown in Figure 4. The first three principal components (PCA(1)-PCA(3)) are presented here. The PCA maps before and after the impact (Figure 4(a, d, g) vs. 4(b, e, h)) show noticeable differences. Their subtraction highlights the presence of abnormal locations due to the impact. However, the abnormal locations are more shown as local spots in the PCA maps; the impact area is not as clear as the shearography result in Figure 3(c). Other advanced thermography processing algorithms may be needed in future studies to achieve more accurate detection of the impact area.

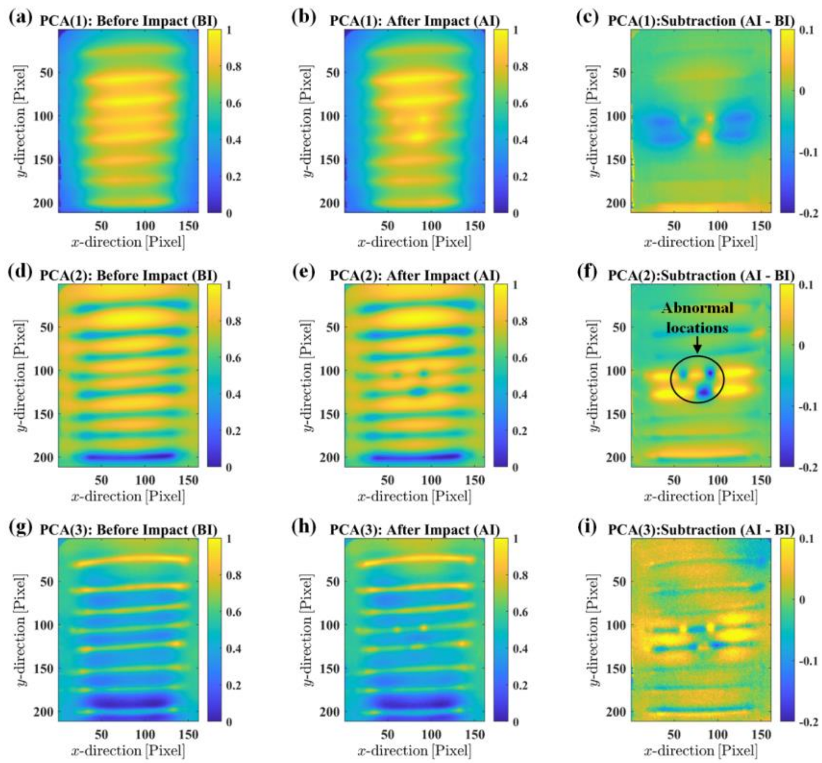

Figure 4. Thermography inspection results on the impacted surface of the GFRP specimen with 8 CNT strips embedded between layers 4th - 5th (The same specimen as in Figure 3).
(a-c): the 1st principal component (PCA(1)) maps before and after the impact and their subtraction.
(d-f): the 2nd principal component (PCA(2)) maps before and after the impact and their subtraction.
(g-i): the 3rd principal component (PCA(3)) maps before and after the impact and their subtraction.

4. CONCLUSIONS

In this work, we presented inspection results from both shearography and thermography on CNT-embedded smart fiber-reinforced composites with impact damage, evaluating the efficacy of defect detection using CNTs as heating sources. The results show that impact damage can be detected from both shearography and thermography inspection results. However, the structural features due to the presence of the CNT strips may affect the defect detection. This can be seen in both shearography and thermography results. Subtracting a baseline map (e.g., before the impact) can compensate for the structural features of the CNT strips and therefore can improve the detection. Future work can be to develop new compensation methods to remove the structural features for defect detection including advanced algorithms for defect area estimation for thermography. In the future, we also aim to develop a novel demonstrator of a composite aerospace structure with integrated CNT-doped sensors that support NDT and enable self-sensing and in-situ SHM capabilities.

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