Hindawi
Journal of Engineering
Volume 2018, Article ID 8260298, 7 pages
https://doi.org/10.1155/2018/8260298

Research Article

The Continuous Monitoring of the Health of Composite Structure

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Received 5 May 2018; Revised 6 July 2018; Accepted 25 July 2018; Published 1 August 2018

Academic Editor: Yuanxin Zhou

Currently nondestructive testing techniques for composite aircraft structures are disadvantaged when compared to instant structural health monitoring (SHM) systems that monitor the structure while being in-service and give real-time data. This paper reports on the use of Polyvinylidene Fluoride (PVDF) sensors in sensing (or monitoring) and locating the defect of a flexible composite structure. The samples used for the tests were manufactured through the use of vacuum infusion process. The three-point bending test was performed to determine the material properties. The vertical sample deflection was measured through the use of vertical height Vernier. It should be noted that the samples were analyzed as cantilever beam due to limited availability of test equipment. The sample health was monitored through the use of PVDF sensor. The sensor data was logged and recorded through the use of Fluke-View scopemeter. The 50 g mass pieces were used as a mode of subjecting the structure to the vertical load. The experiment was performed on samples with defects (drilled 3 mm hole) sample and no-defected sample. The deflection and output voltage from the PVDF sensor of all the samples were comparatively studied.

1. Introduction

The majority of load bearing structural components used in different areas of engineering require periodic inspections of their integrity and assessment of accumulated in-service damage as part of their safety and maintenance requirements. Both costly in monetary terms and down time, these operations can be replaced with a new genre of inspection techniques called active structural health monitoring [1]. This new technology requires the placement of sensors in the structure permanently that can be interrogated continuously or periodically or as the need arises. There is a rise of the development of composite structural health monitoring systems in the market globally. The current mostly used damage detection methods in the aeronautic industry include visual as well as localized nondestructive testing (NDT) techniques such as ultrasonic inspection, acoustic emission, radiography, eddy-current, laser ultrasonic, vibration analysis, and Lamb waves [2–4]. The need for quantitative global damage detection methods that can be applied to a complex structure such as an unmanned aerial vehicle (UAV) has led to the development and continued research of methods that can examine adverse changes in the performance of the composite structure while being in-service and provide real-time data. Instant structural health monitoring using Polyvinylidene Fluoride (PVDF) sensors and the development of a procedure for parameter sampling for a UAV wing structure would be of interest to the aeronautic industry [5, 6]. Structural health monitoring of smart composite material by acoustic emission was investigated using the ceramic piezoelectric sensor known as Lead Zirconate Titanate (PZT) [7]. This work however looks at the feasibility of using a polymeric piezoelectric sensor because it is flexible as compared to PZT, which is brittle [8]. In order to achieve a workable instant structural health monitoring system for use in the aeronautic industry, critical objectives must be achieved. These include the following:

(i) Identifying the type, make-up, and material properties of the composite to be used

(ii) A method for an instant determination and identification of damage

(iii) Determining the geometric location of a particular flaw through the use of a specific sensors and developing a location algorithm to determine where the flaw is located in the overall structure

(iv) Quantification of the severity of the flaw with the use material properties, fracture mechanisms, and damage mechanisms

(v) Prediction of the remaining life of the overall flawed structure.

2. Related Literature

Composite materials are made up of two or more different materials at a macroscopic level to form new properties that cannot be achieved by those individual components in isolation. They have reinforcing and matrix phases. When compared to traditional metallic materials, composites have the advantage because of low density, high strength and stiffness, long fatigue life and high wear, creep, temperature resistance, and corrosion [9]. A vibration technology of combining advanced sensors with intelligent algorithms to continually interrogate structural health condition and provide real-time and instant damage detection can be achieved in structural health monitoring (SHM) [10]. The vibration technology can be analyzed using different approaches and parameters, i.e., natural frequency analysis, scale wavenumber, Fourier Spectral Method, mode and shape method [11–18]. This technique has potential benefits of improving safety, reliability, reducing lifecycle costs and assists in the design of composites structures. Different sensors are integrated and attached to the host structure to monitor structural integrity such as stress, strain, and temperature. The popular sensors that are used in structural health monitoring and give instant information are the following: strain gauges, fibre optic sensors (FOS), eddy-current sensors, micro-electro-mechanical systems (MEMS) sensors, and piezoelectric sensors [19]. SHM technology has advantages and disadvantages and the final choice of the sensor will always depend on a particular application.

The sensors themselves have a load bearing ability and SHM system is greatly simplified compared to other techniques. SHM methods can either be passive or active depending on whether the actuator is used. Passive SHM only attends to the structure and does not interact with it while, in active SHM, the structure is excited with an actuator and interrogated by analyzing the received responses. The common active SHM methods are Lamb wave, electromechanical impedance, and active vibration-based methods, the one used in this study [20]. The common passive SHM methods include acoustic emission, strain-based method, and comparative vacuum monitoring (CVM) method. Active sensors are the ones which respond to strain by the output voltage proportional to the strain but capable of producing strain when voltage is applied to them. Passive sensors are the ones that respond by changing their electrical resistance or optical characteristics or magnetic properties when strained [21].

As mentioned earlier in [9, 10], SHM can be performed in either passive or active methods depending on whether the actuator is used on not. The typical passive approaches include acoustic emission (AE); strain-based and the active approaches include Lamb waves, electromechanical (E/M) impedance, and active vibration-based method. Acoustic emission is a sudden release of local strain energy due to change in structural integrity; this energy is released in a form of transient elastic wave. These waves originate from the AE source and captured by the sensor which is then converted to an electrical signal for interpretation to evaluate structural condition as mentioned in [22]. Strain-based method uses strain gauges and fibre optic sensors to measure strain distribution and is normally based on an array of multiplexed Fibre Bragg Grating. Lamb waves are usually excited and received by PZT or PVDF. FOS also has ability due to multimode and dispersion characteristics but propagation of Lamb waves is complicated. E/M impedance is based on a feedback mechanism; it is a ratio of applied force to the resulting velocity that can be affected by defects, being direct measurement of it is complex. Active vibration-based method is the easiest one in SHM because it can be used for either numerical analysis or experimental analysis. It is recommended for complex and large structures because of practical measurements. It uses a vibration response to detect defects in a structure [23–25].

Polyvinylidene fluoride is a thin flexible polymer which has a low density and excellent sensitivity yet it is mechanically tough [26]. PVDF sensor is well suited to strain sensing applications requiring very wide bandwidth and high sensitivity [27]. The voltage generated by the sensor is collected by the conductive coating on both sides of the sensor film. If the sensor output is proportional to the changes in surface displacement, then the PVDF can be used to detect and monitor behaviour and stresses acting within a material. Like strain gauges the PVDF film needs to be firmly secured on the material under stress in order to translate the material's displacement into a strain in the PVDF film [28]. Piezoelectric sensors are used for measuring low and high frequency vibrations such as Lamb waves or acoustic emission and they are more desired for SHM because of their light weight, size, and low cost. They can be employed as actuators and sensors especially Lead Zirconium Titanate (PZT) ceramic which has excellent sensitivity as a sensor and strong driving abilities as an actuator because of its high piezoelectric constant. PZT is a ceramic [29]; it is brittle so it can easily break if attached to flexible structures. PVDF on the other hand is a polymer that is flexible with large compliance and poor inverse piezoelectric properties; it is best used as a sensor [30, 31]. SHM technologies are being reported as the promising alternative technologies in monitoring the structural health through the use of sensors and they are described as the self-monitoring technique with a greater security potential [32, 33].

This paper reports on the flexible system driven by the PVDF sensor to continually monitor the health of the composite structure. The system is designed such that it detects and locates the defect on the structure. The presence of the defect and its location are being indicated by the voltage output which is linearly related to the structural deflection. The detailed explanation of the system is presented under

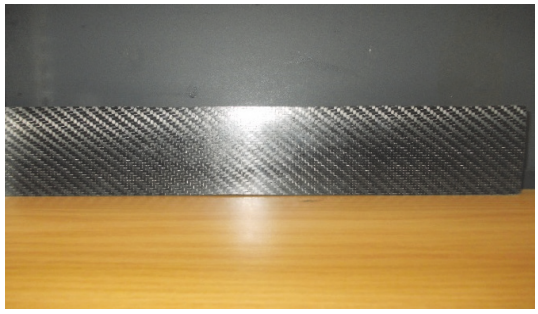

Figure 1: Defect-free composite sample.

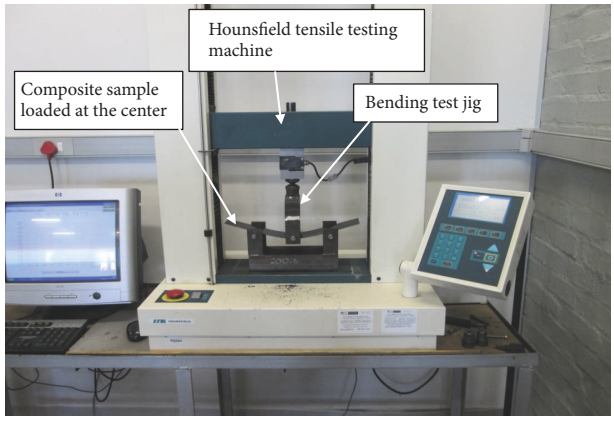

Figure 2: Three-point bending test.

results section of this paper. The external attachment of the sensor is to avoid tempering with the strength of the structure.

3. Experimental Procedure

The samples used for this experiment were manufactured through the vacuum infusion process. The resin and carbon fibre was used to manufacture the samples of composites that resemble the unmanned aerial vehicle (UAV). We used the composite structures due to the fact that most UAV wings are made out of composite materials. Sixteen samples were produced from vacuum infusion process and all had the same dimensions of 280 mm × 69 mm × 2 mm (see Figure 1). The idea of producing the high number of samples was due to the fact that some samples were to be used for failure analysis.

There were three bending tests (three-point bending) performed in one sample. The three-point bending tests were performed through the use of Hounsfield tensile tester machine. Figure 2 shows the first experiment which was performed so as to find Young's modulus of the samples. Figure 3 shows the second bending experiment which incorporated the PVDF sensor. The purpose of incorporating the PVDF sensor was to find the voltage at the fracture point. This voltage would be used as the flag to activate the alarm system when the full system is installed to the real application. Two samples (one with sensor and another one without a sensor) were bent until they fail while the other two were bent to the point before they fail and their properties were recorded. Figure 4 shows the image from shearography of the defect-free sample. The shearography image of the sample with defects is shown in Figure 6. Figure 6 presents the results for the failed sample shown in Figure 5. The shearography records the whole sample and thereafter gives two dark round contour plots in the location with defects.

The cantilever beam deflection experiment followed after the three-point bending tests. The idea behind the performance of the deflection test experiment was to test the capabilities of the PVDF sensor in continuously monitoring the structural health (see Figure 7). Four samples were used in performing the deflection tests. The 3 mm holes were drilled as the defects to the three samples while the other one was defect-free. The first defect was located 50 mm from the fixed end of the cantilever beam, the second defect was located 100 mm away from the fixed end, the third defect was 150 mm away from fixed end, and the last one was at 200 mm away from fixed end. All the four samples had PVDF sensor attached at the middle of each sample. The samples were loaded (using nine 50 g mass pieces) towards the end of the free end of the cantilever beam. The specimens' deflection was measured using the digital height Vernier.

The 50 g mass piece was hung towards the free end of the beam using the mass piece hanger and the beam deflection and the PVDF sensor voltage output were recorded. The load

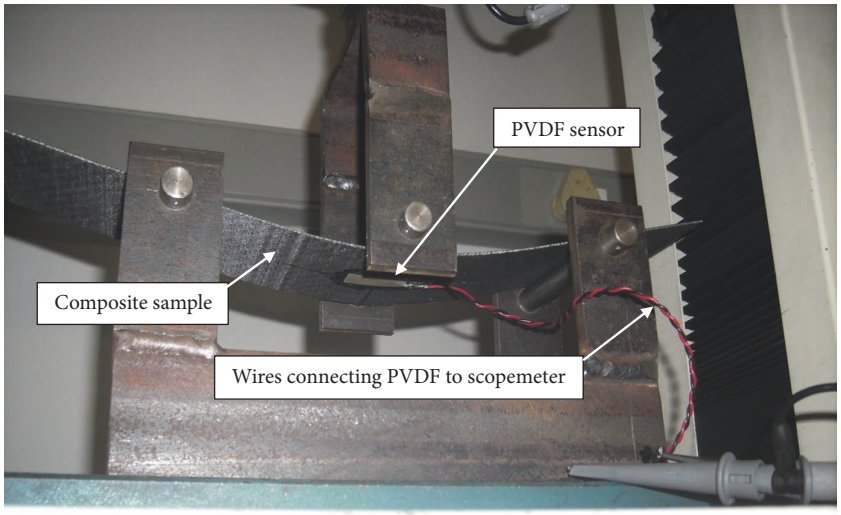

Figure 3: Three-point bending test with PVDF sensor.

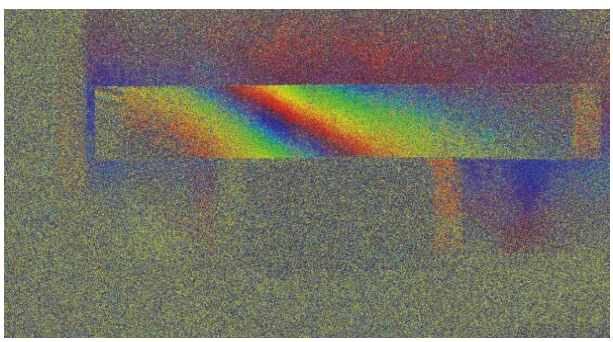

Figure 4: Shearography image of defect free sample.

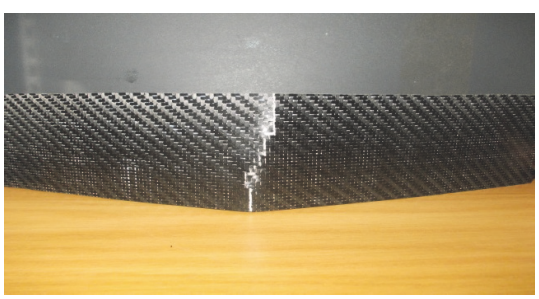

Figure 5: Sample failed after bending test.

was increased in steps of 50 g until 450 g and all the output was recorded.

4. Results and Discussion

The beam deflection data is graphically represented in Figure 8. It could be seen from the figure that the defect-free beam deflects less than the beams with defects. This suggest that the beam's stiffness decreases due to the presence of defect. The beam with defect close to the fixed end deflects higher than all the beams and this is due to the fact that the defect is very close to the location with high stress concentration.

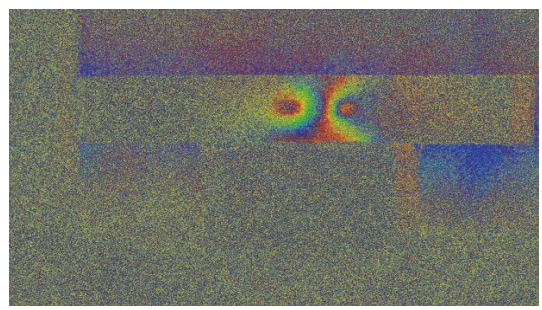

Figure 6: Shearography image of the failed sample.

Figure 9 shows the graphical representation of the voltage output from PVDF sensor based on the input load. The trend notable from the deflection results is also noticed in Figure 9. The sample with the defect located 50 mm from the fixed end yields high output voltage. This indicates that the presence of the defect on the sample weakens the strength of the sample. The higher output voltage suggests higher sample deflection. The variation of PVDF sensor output voltage suggests the presence of the defect on the sample

5. Conclusion

The composite samples were successfully manufactured using the vacuum infusion process. The samples were prepared for different tests mentioned in the previous sections. The PVDF sensor was successfully installed to the samples with the purpose of testing its capabilities in monitoring the structural health. The PVDF sensor has demonstrated the capabilities in detecting the presence of the defect on the structure

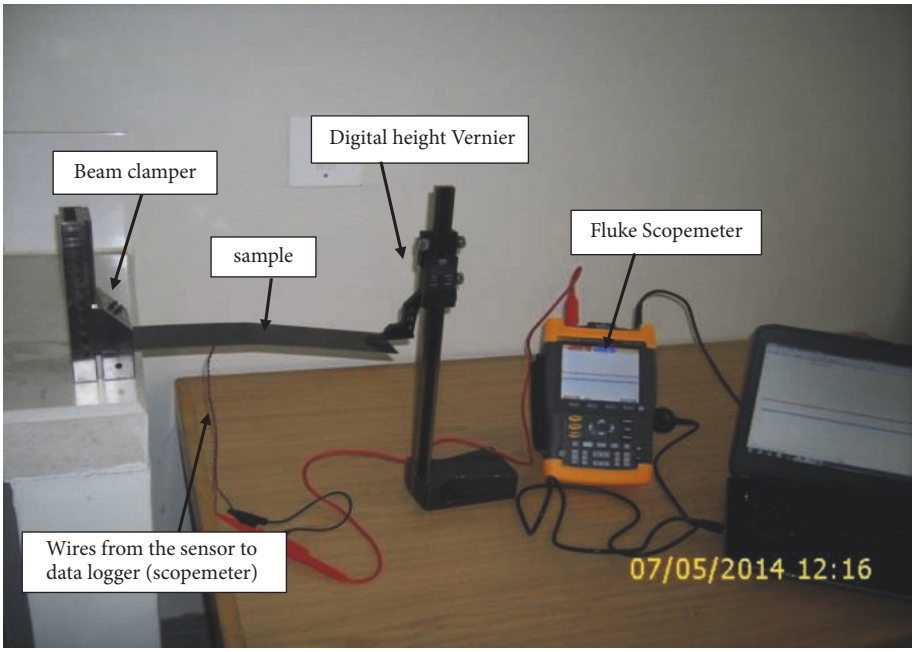

Figure 7: Deflection test setup.

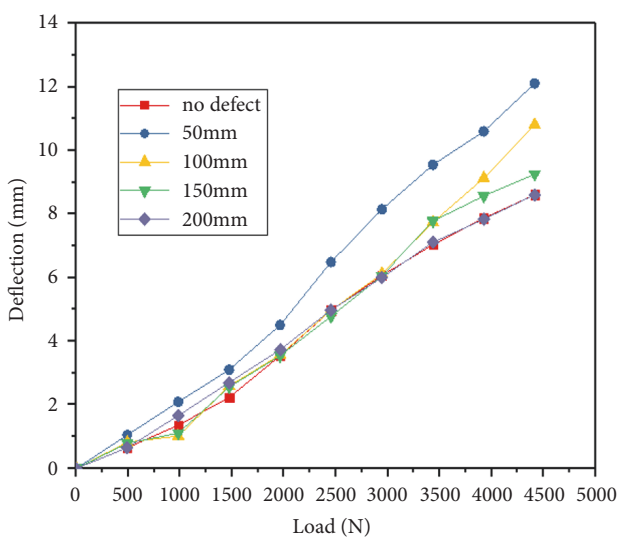

Figure 8: Load-deflection curves for defect-free beam and beams with defects.

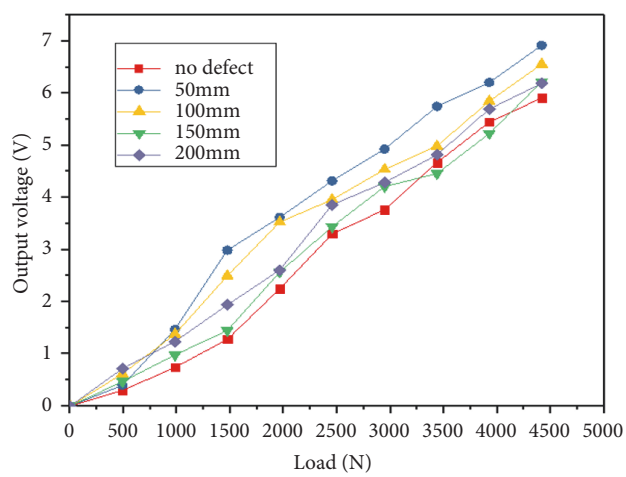

Figure 9: Load-output voltage curves for defect-free beam and beams with defects.

through the output voltage variation. The voltage variation is in agreement with the deflection variation of different locations of the defects. The conclusion drawn from this work is that the PVDF sensor has the capability of detecting the defect on the composite structure and it can accurately locate the position of the defect.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest that may arise from this work.

Acknowledgments

The authors would like to acknowledge AMTL for allowing them to use the facilities in manufacturing samples. The authors would also like to thank Mr. Moni for assistance with the bending tests.

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