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Piezoelectric fiber composite transducers for health monitoring in composite structures

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ABSTRACT

This paper presents a critical study on the sensing characteristics of piezoelectric fiber composite transducers (PFCTs), in order to evaluate them as an effective embedded sensor inside the composite structures to monitor the stress/strain concentration levels at the critical locations. The functions of PFCT as an embedded sensor inside the composite structure are threefold: (i) to detect all loading conditions acting on to the structure, (ii) to predict the occurrence of damage while in-service under dynamic loads, and (iii) to monitor the pre-existing damages in the composite structures so that the severity can be ascertained to avoid eventual catastrophic or brittle failures. PFCT will be an ideal choice for composite structures applications, as they are highly flexible, easily embeddable; their high compatibility to the composite manufacturing techniques, and more importantly, it is expected that they will produce significantly less interfacial stresses when embedded inside the composite structures.

Two types of PFCTs (macro fiber composite (MFC – from Smart Materials Corp.), and piezoelectric fiber composite (PFC – from Advance Cerametrics Inc.)) have been selected and calibrated by investigating their sensor performances based on characteristics; like transfer function, sensitivity, nonlinearity, resolution, and noise levels. Dynamic loads (transverse and longitudinal) have been applied and their corresponding output response is evaluated. The sensitivity of these products to the changes in frequencies and strain levels of input dynamic loads is investigated through the constant strain and frequency curves. Healthy voltage output response is observed even at low strain level domains, which indicates their high sensitivity and high resolution as a sensor. Comparing the results, it can be concluded that these sensors demonstrated their superior sensitivity and better performance over the traditional strain gauges. After a detailed sensor performance assessment, a case study has been conducted on the composite beam structure, where the ability of the PFCTs to detect the delamination of various levels inside the composite beam structure through modal analysis has been investigated. Then tests were performed to investigate the ability of the embedded PFCT sensors to detect the changes in the applied input mechanical stress/strain when embedded inside glass fiber–epoxy composite laminate samples. It is found that these sensors are effectively able to detect the changes in the applied input mechanical stress/strain. A linear relationship has been observed between the applied input mechanical stress and the sensor generated voltage output.

1. Introduction

Composite structures have been developed and used for modern aviation, military, and civil applications for over 50 years. The major advantages of composites over metals are: (i) higher stiffness to weight or strength-to-weight ratio, (ii) higher resistance to fatigue damage and harsh environments, (iii) repairable, (iv) provides design flexibility, and (v) lighter in weights. Typical aircraft composites are not ductile; they are brittle, which means they undergo relatively minor permanent deformation prior to final failure. Composite structures are also subjected frequently to external excitations over a variety of vibration frequency ranges. Such dynamic interference may cause the structures to suffer from fatigue damage and/or catastrophic failures if the excitation frequency approaches to the natural frequency of the structures, causing resonances in the structure. The practical functionality of composite structures is not possible without assembling them appropriately. Commonly, the assembly of such structures is done by using mechanical fasteners or an adhesively bonded strap joint. The introduction of mechanical fasteners inside the structure leads to the severe rise in the localized stress concentration levels due to

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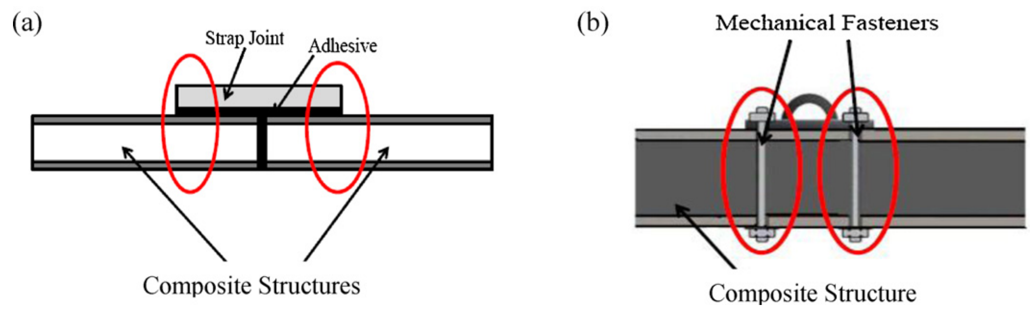

Fig. 1. High stress concentration regions (circled in red) in the composite structure assembled by: (a) adhesively bonded joint and (b) mechanical fasteners. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

material discontinuity. These high stress concentrations may trigger the fatigue cracks initiation sites and will ultimately lead to the failure of structures [1–8]. In an adhesively bonded joint the loads between the adherents and adhesive are always transferred in the forms of shear and/or peel stresses through the adhesive layer, thus the high stress concentrations level in the end regions of the adhesive interface bond lines are the main reason for the bond failure [9]. Fig. 1 shows the locations of the high stress concentration regions (circled in red) in the composite structure assembled by mechanical fasteners and adhesively bonded joint. Hence composite structures require a Health Monitoring System, which could monitor continuously the stress/strain concentrations at critical locations of composite structure.

Composite structures with integrated sensors offers unique capabilities: monitoring the manufacturing process of composite parts, performing nondestructive testing once fabrication is complete, and enabling real time health monitoring and structural control. An effective sensor could perform the following functions through its sensing characteristics: (i) to monitor the integrity of the structure continuously, (ii) to monitor the pre-existing damages, and (iii) to predict the onset and location of the damages in the structure. The basic requirements for such sensors are compactness; large area monitoring capability, minimal electrical interconnection, easily embeddable, and compatibility with composites and composite manufacturing techniques.

Piezoelectric (PZT) materials have been extensively used in the design of many self-adaptive smart structures because of their excellent electro-mechanical coupling behavior. The experimental results of various research groups have confirmed that piezoelectric material can be effectively used for vibration control, noise suppression, precision alignment control, energy harvesting, sensing, and for damage detection applications [10–19]. In these applications PZT ceramics are commonly used due to their relatively low cost, high band-width and good actuation capabilities. But the major drawbacks of these ceramics are their high brittleness and low flexibility, which has blocked their extensive applications in engineering. In order to overcome this problem piezo-composite transducers were developed. A typical piezo-composite transducer is made of an active layer sandwiched between two soft thin encapsulating composite layers as shown in Fig. 2. The electrodes of the piezo-composite transducers can be of two types: (i) continuous electrodes, and (ii) interdigitated electrodes. The piezoelectric fiber composite transducer (PFCT) comes under the category of piezo-composite transducers, which are manufactured by embedding piezoelectric fibers into a composite matrix along one specific direction. The PFCTs will be an ideal choice for many of composite structures application, as they are highly flexible, easily embeddable; their high compatibility to the composite manufacturing techniques, and more importantly, it is expected that they will produce less interfacial stresses when embedded inside the composite structures.

Experiments are performed on two PFCTs: macro-fiber composite (MFC-2807-P2 from Smart Materials Corp.) and piezoelectric fiber composite (PFC-W14) form Advanced Cerametrics Inc. PFC is made from circular shaped PZT fibers with a diameter of 250 μm, whereas MFC is made from square shaped PZT fibers with dimensions of 250 μm × 250 μm. Although both MFC and PFC products show similar characteristics and dimensions apparently but there are subtle differences between these two products. The major differences between these two sensors are as follows:

(i) PZT fibers cross section
  Macro fiber composite sensor (MFC) contains the piezoelectric fibers with square cross-section. Piezoelectric fiber composite sensor (PFC) contains the piezoelectric fibers with circular cross-section. The square cross-sectional rod will need more materials and will be less cost-effective than circular cross-section.
(ii) Cross section area/active area of the sensor
  MFC sensors have the active PZT fiber cross-section area of about 70,650 μm^2. PFC sensors have the PZT fiber cross-section area of about 96,162.5 μm^2. PFC sensors have more active area when compared to MFC sensor; hence they will be producing more output voltage response for the same amount of the strain applied.
(iii) Electric field distribution
  Another important difference between both of these sensors is the electric field distribution along the sensor thickness as the fiber cross-section (square and circular) is different in both of these sensors.

Fig. 3 shows the constructional information of the MFC and PFC products with interdigitated electrode layers. The presence of the damages in the structure may degrade the integrity, stiffness, strength, and fatigue properties of composite structures severely.

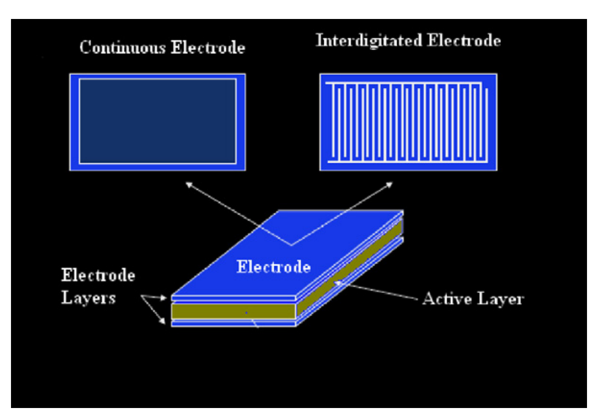

Fig. 2. Piezo-composite transducers with surface electrodes.