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Characteristics and fabrication of piezoelectric GFRP using smart resin prepreg for detecting impact signals

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ABSTRACT

To develop a composite that also functions as an impact sensor, a piezoelectric glass fiber-reinforced polymer (GFRP) was fabricated using a mixture of $Pb(Ni_{1/3}Nb_{2/3})O_3$-$Pb(Zr, Ti)O_3$ (PNN-PZT) piezoelectric powder and epoxy as a smart resin. Prepreg sheets were prepared by impregnating glass fiber with the smart resin and the specimen was fabricated by autoclave molding. To utilize the composite as a sensor for detecting impacts, electrodes were added to the two sides of the composite, and the specimen was poled briefly at room temperature to activate its piezoelectric properties. A calibrated and instrumented impact test was conducted to demonstrate impact response and measure the sensitivity; a signal processing device was developed that matched the high impedance of the piezoelectric GFRP. The sensitivity of the piezoelectric GFRP sensor was measured by comparing the impact force signals from an impact hammer with the corresponding output voltage from the sensor. The threshold for detection of impacts was below 15 N. The tests confirmed that the piezoelectric GFRP itself could be utilized as an impact sensor.

1. Introduction

Composite structures combine two or more materials in order to improve on their material properties; the familiar fiber-reinforced polymer composites are made by impregnating a high-strength fiber material (such as glass, carbon, or aramid) with a polymer resin (such as epoxy) that is subsequently cured. Advantages of these composite structures are low weight and excellent specific strength, stiffness, and environmental resistance. Composites are widely used in the aerospace field where low weight is vital, and in the construction, defense, automobile, marine, and electronics industries; the applications of composites are continually expanding. However, with their growing use, it is also becoming important to ensure the safety of composite-material structures in operation.

For example, many wind farms have recently been introduced as part of the renewable energy supply. In order to increase the efficiency of energy production, the blades are made larger and lighter by using composites. In addition, these large composite structures may be poorly accessible, as they are often installed in extreme areas such as coastal, maritime, and alpine areas, which are chosen to create an operating environment away from concentrations of population. Failure or breakage of the structures may occur for a variety of reasons, such as bird collisions, lightning, and hailing. Because of these various environmental risks, the use of real-time monitoring or structural health monitoring (SHM) technology to record the time and the extent of impacts or other events on the composite structures has increased to ensure efficient maintenance and reliability of the system.

Various types of sensors such as piezoelectric ceramics, strain gauges, and fiber Bragg gratings (FBGs) are used to monitor the condition of large composite structures such as wind turbine blades or airplanes [1]. Among these sensors, piezoelectric ceramic sensors have a very high electro-mechanical conversion efficiency, and therefore have the high sensitivity needed to detect signals from small impacts. Piezoelectric ceramic sensors are relatively easy to install, but they are difficult to apply to structures of complex shapes and those with large strains. In addition, a ceramic sensor could easily be broken if a shock were applied directly. To obtain a meaningful signal, a filtering technique that can block spurious background signals resulting from the high sensitivity of the sensor is needed. Strain gages are inexpensive, have high reliability of their measured data, and are highly stable due to their resistance to environmental factors. However, strain gauges can be damaged by excessive deformation or repeated loading because the range of strain that can be measured is small ($< 5\%$). In comparison, the FBG sensor, which reflects light of a specific wavelength, has a high signal-to-noise ratio (SNR) and low signal loss. Although it can easily measure simultaneously at many locations, commercialization has been

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Table 1
Comparison between commercial sensor types used for detecting events and monitoring conditions in structures.

Sensor type	Strength	Weakness
Piezoelectric ceramic sensor	High sensitivity to event signals	Difficult to apply to complex shapes and large detection areas
	Easy installation	Fragile against external shocks
Metal foil strain gauge	Inexpensive cost	Difficult to measure large deformations
	High reliability of the measured data	Difficult to measure repeated loads
	High environmental resistance	
FBG sensor	High SNR and low signal loss	Frequency deviation from changes in temperature, humidity, and external environment
	Measure at many positions simultaneously	

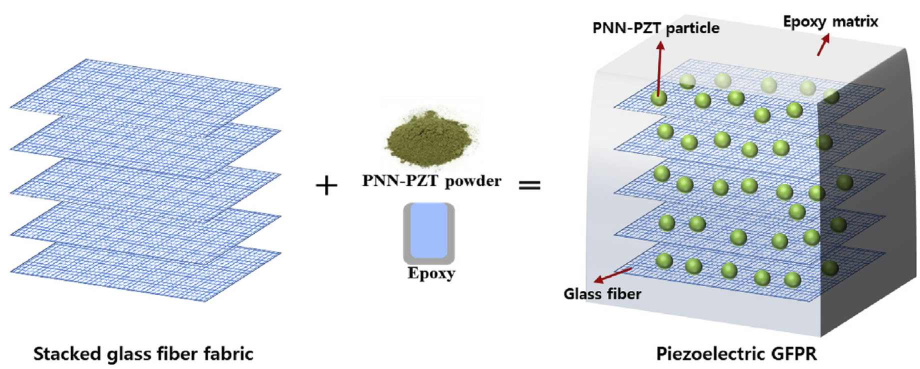

Fig. 1. Schematic of smart prepreg, consisting of smart resin (PNN-PZT in epoxy resin) and glass fiber.

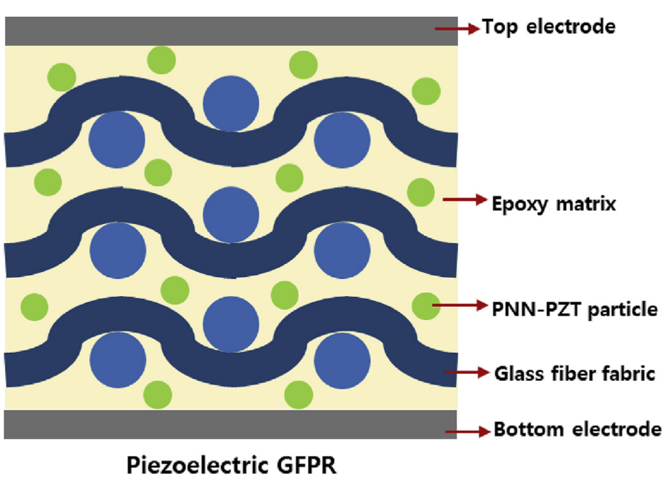

Fig. 2. Schematic of piezoelectric GFRP using prepreg made of smart resin.

difficult as a result of frequency sensitivity from changes in temperature, humidity, and the external environment [2]. A summary of commercial sensor characteristics for detecting structural events is shown in Table 1.

Various types of sensors can be used to detect signals from structural events but they affect manufacturing costs if the additional sensors are installed after the structure has been fabricated. The efficiency of the structure's operation can be reduced, as the aerodynamic characteristics will be degraded by mounting the sensor externally. If a sensor dedicated to a certain area malfunctions, the overall monitoring integrity is reduced. To overcome these disadvantages, this research studied a composite-material structure into which a sensor was integrated by use of a smart resin [3–5] that includes an electro-mechanical conversion function; this replaces the conventional epoxy resin so that the composite structure itself can act as a sensor for use in harsh environments. We confirmed that the structure can detect impact signals. As a first step, to investigate the feasibility and practicality of the integrated sensor and composite structure, prepreg impregnated with a smart resin containing piezoelectric materials was fabricated and a composite material was produced using the autoclave molding method. An impact test was then performed to evaluate the sensitivity of the sensor.

2. Experimental

2.1. PNN-PZT powder for smart resin

Piezoelectric materials produce an electrical signal when a mechanical motion or force is applied, and a mechanical force when an electrical signal is applied. By mixing a piezoelectric material with a resin such as epoxy, a smart resin having an electro-mechanical conversion function can be produced (Fig. 1). By then impregnating glass fiber with the smart resin, a new type of composite that has an electro-mechanical conversion function can be fabricated (Fig. 2). This piezoelectric glass-fiber-reinforced polymer (GFRP) requires two electrodes, attached to the two opposing sides, to act as a sensor by measuring the electric charge generated by the piezoelectric material when stressed. $Pb(Ni_{1/3}Nb_{2/3})O_3$-$Pb(Zr, Ti)O_3$ (PNN-PZT) is used as the piezoelectric material, and must be poled (i.e., permanently polarized) prior to use by applying a high electric field between the electrodes. The sensitivity of the composite sensor depends on several factors, among which are the poling field, poling time duration, thickness, and the PNN-PZT percentage in the composite.

Various studies have been conducted to fabricate a composite that functions as a sensor using a piezoelectric material [6–8]. It is important to choose the piezoelectric materials that are appropriate to the various components and shapes and with consideration for the fabrication environment and the structural purpose of the composite. We used the PNN-PZT soft piezoelectric powder which was developed in person for this smart resin because of the following: First, PNN-PZT is a