Composite Materials with Self-Contained Wireless Sensing Networks

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ABSTRACT

The increasing demand for in-service structural health monitoring, particularly in the aircraft industry, has stimulated efforts to integrate self-sensing capabilities into materials and structures. This work presents efforts to develop structural composite materials which include networks of sensors with decision-making capabilities that extend the functionality of the composite materials to be information-aware. Composite panels are outfitted with networks of self-contained wireless sensor modules which can detect damage in composite materials via active nondestructive testing techniques. The wireless sensor modules will communicate with one another and with a central processing unit to convey the sensor data while also maintaining robustness and the ability to self-reconfigure in the event that a module fails. Ultimately, this research seeks to create an idealized network that is compact in size, cost efficient, and optimized for low power consumption while providing a sufficient data transfer rate to a local host.

Keywords: Structural health monitoring, self-sensing, composite materials, nondestructive testing, wireless sensor modules

1. INTRODUCTION

A composite is an artificially constructed material system consisting of multiple components designed to attain specific properties superior to those of the individual constituents. Composites have unique advantages over monolithic materials including high strength, high stiffness, long fatigue life, low density, and adaptability to the intended function of the structure. Because of these properties, composite materials lend themselves to a wide range of applications across numerous industries, and there is a trend of increased use of composites in the aircraft industry. The Boeing 787 Dreamliner has fully half of its airframe materials created using composites.

In many of the applications, failure of the composite in service can be critical. This was clearly evident with the American Airlines flight 587 disaster which resulted in 260 passenger casualties and 5 ground casualties. The failed carbon fiber vertical stabilizer can be seen in Figure 1. Thus, there is a need to rapidly assess the structural health or integrity of a composite.

Figure 1: Failed carbon fiber and epoxy resin vertical stabilizer of American Airlines flight 587.
2. INITIAL APPROACH TO DEVELOPMENT

Initially, this work sought to add properties to the composite itself that are information-based without compromising the structural integrity of the host composite material. This information took the form of structurally integrated microsensors that could monitor and report on the local structural environment on request or in real-time as necessary. The envisioned sensors could read such structural health related parameters as temperature, load, strain, acceleration, or acoustic emissions. This development approach included:

- Embedding microsensors into composite materials
- Adding processing power to form addressable sensor nodes
- Forming networks with efficient processing strategies to locate and assess damage

The increased knowledge of the structure, based on actual data rather than statistical assumptions and extrapolations, would allow for greater flexibility in composite design. The development of a reliable means of ascertaining the status of the composite structure would allow for more high performance designs while minimizing over designing and building in redundancy.

3. FEASIBILITY STUDY

Preliminary work to demonstrate the feasibility and survivability of embedding sensors in composite materials was conducted. A ten by ten array of digital thermometer sensors was fabricated on conventional printed circuit board material with microprocessors programmed to communicate over a network. The substrate and sensors were embedded in an aramid and epoxy composite. The resulting panel and its successful temperature sensing ability are shown below.

Figure 2: Aramid/epoxy composite panel with embedded network consisting of a 10 by 10 array of individually addressable thermal sensors. A hand is placed on the panel (left) generating a thermal image (right).

4. MECHANICAL INVESTIGATION

Essential to the application of smart composites is the issue of the mechanical coupling of the sensor to the host composite material. The thrust of the research presented here was to characterize the effects of embedding sensors on the mechanical properties of the host structural composite material in order to select a sensor and embedding configuration that could seamlessly be integrated into the host composite without compromising the integrity of the structure. The testing configurations included quasi-static tension, tension-tension fatigue, quasi-static short beam shear, and short beam shear fatigue. Further testing details and complete results can be referenced in the related publication³.
Figure 3: Materials utilized in mechanical investigation following the initial development approach.

**Average Fatigue Short-beam Shear Life**

![Graph of average fatigue short beam shear life of composite materials with embedded sensors.](image)

Figure 4: Graph of average fatigue short beam shear life of composite materials with embedded sensors.

Figure 5: (Left) Typical failure of [±45]_{10} samples with embedded simulated sensor. (Right) Micro-crack initiation at sensor and resin pocket eyelet in [0]_{4} at 5% strain.
5. COMPUTATIONAL INVESTIGATION

Both 2D plane strain and 3D FEA models have been developed to analyze the stress/strain state surrounding the embedded microsensors within a unidirectional composite laminate. The objective of the numerical effort was to take into account the observed resin-rich areas caused by embedment and to determine their effects on the local stress field around the embedment and the corresponding potential failure modes.

![Micrograph of a section of S2-glass/epoxy composite laminate with embedded simulated microsensor with local finite element mesh of 2D FEA model overlaid.](image1)

The anisotropic nature of composite materials causes significant attenuation and dispersion of acoustic waves, which brings several difficulties in locating the source of a damage event utilizing acoustic emissions (AE). The application of a triangulation method typically requires a considerable amount of computation and a great deal of intermediate data storage. A look-up table methodology for AE source location was therefore implemented as alternative to the triangulation method. The idea behind of this method is to compare the acquired data while the structure is in service with the pre-calibrated AE behavior of the studied structure. Complete details and results can be referenced in the related publication².

![Schematic diagram of composite panel with PVDF sensors and look-up table calibration grid.](image2)

Figure 6: Micrograph of a section of S2-glass/epoxy composite laminate with embedded simulated microsensor with local finite element mesh of 2D FEA model overlaid.

Figure 7: Schematic diagram of composite panel with PVDF sensors and look-up table calibration grid.
6. CURRENT APPROACH TO DEVELOPMENT

The basis of the current development approach is an active monitoring technique that utilizes acoustic detection of damage. The fundamental strategy is to fabricate a network of wireless sensing modules that are capable of both sending and receiving acoustic signals. In practice, each module will send a signal to the nearby modules. Then, by comparing the current waveform to an established baseline waveform, determine if there have been changes indicative of damage to the structure. This approach is essentially a permanent wireless acoustic nondestructive testing (NDT) system.

Figure 8: Active in situ nondestructive testing system diagram.

Figure 9: Self-contained wireless sensor module (wsm).

The advantages of the in situ NDT system include:

- The power requirements are greatly reduced because the wireless sensor modules need only be active for the short duration when the local region is being tested.
- The wireless bandwidth requirements are greatly reduced because the communication need only be between the few active wireless sensor modules.
- The active in situ NDT system offers the ability to observe long term deterioration or damage without the need for constant monitoring.

There are some increased demands this approach places on the system, including:

- The transducers and associated electronics must be stable over a long period of time since it is a comparison to an established baseline value that is important.
- To make accurate measurements, accurate timing between neighboring wireless sensor modules must be maintained, and there are a variety of schemes to achieve this, with the choice depending upon the actual wireless protocol implemented.
7. CONCLUDING REMARKS

The goal for the first phase of the current development approach for this project is to create a 4 by 4 array of wireless sensor modules on an actual composite panel from an aircraft. Currently, two wireless sensor modules, shown in Figure 9, along with radial shear sensors on each module have been used to successfully send and receive ultrasonic signals. A third control module connected to a PC is used to configure the module to either be in transmit or receive mode, trigger a test, and collect the received data from the module. Additional modules have been manufactured to scale up the experiment so that an array of modules can be used to collect data.

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REFERENCES


