INTRODUCTION

The desired static performance and dynamic adaptability of advanced structural materials demands the development of intrinsic analysis and control systems which are capable of independently optimizing structural properties in response to particular external disturbances. Materials and structures which incorporate environmental and material sensors, mechanical actuators, and electronic signal processing and adaptive control systems to produce either appropriate readouts or actuator responses for particular sensor inputs have been termed "smart", "intelligent", "sense-able" or "organic" during the past several years [1]. The primary advantage of such materials and structures is that they may be designed to adapt to a wide range of conditions during their normal use lifetimes. Some types of sensors and actuators, particularly small and lightweight optical fiber sensors and shape memory metal actuators, may be directly embedded without seriously affecting material integrity. Additionally, the optical fibers embedded in such material systems may be used as life cycle sensors to monitor nondestructively the way in which composite and metal structures are fabricated, the inservice lifetime performance conditions of the material, and the onset of material degradation due to a variety of causes including fatigue and impact damage [2].

The following sections are intended to briefly outline our work and the related work of a number of research groups in the smart structures area. Specifically, we will consider the effect of embedded optical fiber sensors upon the internal mechanics of the host material, the development of optical fiber sensors for strain and vibration measurement, and the potential use of fiber sensors to determine the onset of material and structural degradation.

EMBEDDED SENSORS IN SMART MATERIALS

Central to the smart structures scenario is the concept that sensors, actuators, power conduits and electronic circuitry may be incorporated within structural building blocks to provide an internal nervous system capable of recognizing and responding to environmental changes and
reacting to damage and the onset of material degradation. If such a scenario is to be implemented in practical aerospace, marine and transportation structures, all of these system components must be embedded within or attached to the material in such a way that its structural integrity is not compromised.

The use of embedded optical fiber sensors in advanced fiber-matrix composites is particularly attractive because the optical sensor fibers, although larger, have the same geometry as the structural fiber elements. The embedding of optical fibers in such materials has been considered by several investigators. Preferred optical sensor fiber orientation within multi-ply composite laminates is determined by the intended application of the sensor. Udd, Measures and their co-workers have considered fiber orientation specifically for the minimization of the resulting perturbation to the laminate [3] and the detection of impact damage via the observation of optical fiber breakage [4], respectively. Part of our recent related work at Virginia Tech has involved the design and fabrication of fibers having novel geometries, although still capable of desired sensing operation, and novel fiber coatings which provide both protection from handling as well as an improvement in the mechanical and chemical coupling between the core and cladding waveguide structure of the fiber and the composite matrix [5]. Partially as a means of testing those fiber and fiber coating designs, we have modeled and directly measured the internal micromechanical effects resulting from optical fiber embedding. Representative results of those measurements, obtained using Moire imaging techniques, are given in Figure 1. This interferogram of the side of a graphite/epoxy coupon containing a single 50/125 glass-on-glass optical fiber near its center may be interpreted visually to determine the two-dimensional variation of the strain component parallel to the applied load. A series of measurements similar to these but obtained for different load levels on the composite specimen indicate strain concentrations of approximately 0.05 at the fiber-to-matrix boundary for an applied load equal to half the failure load of the sixteen-ply specimens tested. These large interface strain concentrations may pose significant limits on the long term structural integrity of materials containing embedded sensor fibers. Moreover, these results suggest that basic mechanical modeling and measurements are required to quantify the effect of the embedment of sensors as well as other control system elements within selected materials chosen for applications in smart structures.

OPTICAL FIBER SENSORS FOR MATERIALS NDE

This section briefly outlines the potential and demonstrated use of embedded optical fiber sensors for the monitoring of material fabrication conditions and the nondestructive post-fabrication sensing of environmental conditions.

Composite Cure Monitoring Applications

Material cure or fabrication monitoring is the first application of internal sensors as part of complete life cycle testing. In situ fiber optic cure monitoring has been investigated for several years by Levy [6] who used distal end fiber components capable of indicating changes in both curing adhesive color and index of refraction. More recently, Afromowitz [7] has demonstrated the in-line adaptation of similar elements which can be addressed via through transmission in an optical fiber instrumentation system. Extensions of this type of sensor instrumentation may allow the distributed measurement of the index of the curing matrix material throughout large workpieces of varying thicknesses [8].
Our work in this area has been concentrated in the area of "sensitive-clad sensors" (SCS) which are capable of direct localized sensing of the cure process via the implementation of modified waveguide cladding/coatings. Glass-on-glass fibers are acid etched to remove the clad, then re-clad and coated with a layer or layers of appropriate polymers capable of effectively coupling to the glass core and interacting with the surrounding curing matrix in such a way that the wavelength transmission function of the "sensitive clad" region of fiber changes as a function of cure [5]. A simple sketch of a single SCS element is shown in Figure 2. The use of this type of sensor is intended to allow the in situ monitoring of reaction path throughout the cure process and throughout the workpiece.

Temperature, strain, and compaction pressure may be measured during materials processing using fiber sensor systems similar to the interferometric configuration shown in Figure 3. Analysis indicates that for shot noise limited detector performance, a 1.0Hz bandwidth, and reasonable laboratory equipment parameters, the minimum detectable strain
Figure 2. Sensitive-Clad Sensor element core and modified clad/coating geometry.

Figure 3. Differential fiber interferometer arrangement for heat flow measurement in materials.

is on the order of micro-microstrain per centimeter of fiber sensor length [9]; this demonstrates the excellent sensitivity of interferometric fiber sensor devices. Although conventional interferometric fiber sensor designs are impeded by indistinguishable multiparameter influences on output signal response, alternative configurations which we have studied avoid such problems by compensated mechanical designs or post-detection signal processing [10, 11].

**Structural Analysis Applications**

The in-service performance of structures fabricated with internal sensors may be evaluated using those sensors. Many authors have considered the development of optical fiber sensors for this type of evaluation [12]. Our group has specifically placed most emphasis on the research of optical time domain and fiber modal domain sensor systems, system components, and their evaluation.
Optical time domain reflectometry (OTDR) techniques may be used to measure both distributed and localized strain in structures [13]. Our efforts here include both amplitude and time measurement methods. Our early work utilized the principle of transmitted optical power attenuation due to the localized bending of optical fibers embedded within composite materials [14, 15]. Because the spatial transient distance of most optical fibers is larger than the desired spatial resolution, this OTDR method is not applicable to high resolution system implementation which may be necessary in some smart skins applications.

Alternatively, partially reflecting splices may be inserted along the length of a sensor fiber and OTDR methods used to determine the time of arrival of the optical pulses reflected from each splice [16]. Since position changes in such splices produce variations in the times of arrival of the pulses from the splices, observation of the time dependent arrival times yields the distributed strain. Extensions of the use of basic in-line splices for the measurement of strain between adjacent splices are 1) the multiplexing of a network of fiber sensor arms with adequate time delay length fibers between the arms of permit time domain separation of back reflected pulses and subsequent resolution of two-dimensional strain distributions, 2) the use of fiber-to-fiber intensity coupling loss in a single strained splice housing to determine strain localized to the vicinity of the housing, and 3) the low-profile packaging of in-line splices to permit the embedding of such sensors within advanced composite materials [17].

Another sensor method developed for the in-service lifetime monitoring of materials measures the interference between two or more modes in a few mode fiber [18]. We have applied such sensors to the detection of quasi-static strain, low frequency structural vibrations and relative high frequency stress waves [19]. For the evaluation of structural vibrations such as those of the panel shown in Figure 4, it can be shown that the output signal from a modal domain sensor may be interpreted to yield the mode shape amplitudes of the vibrating structure's mechanical response [20]. This type of response is essential for the type of vibration damping control described below.

Modal sensing has also been applied to the detection of stress waves generated by acoustic emission (AE) events in mechanically loaded graphite/epoxy specimens. The observed risetime of such systems is on the order of 1.0 microsecond [21].

![Figure 4. Modal interferometer system for structural mode shape amplitude detection.](image-url)
NDE SIGNAL MULTIPLEXING AND PROCESSING

Smart skins sensing using embedded optical fibers may require signal multiplexing and processing if good spatial resolution is desired and the volume of material to be evaluated is large. Arrays of attached or embedded fibers, for example, have been proposed to indicate impact damage and the multiple signals from such arrays inherently require some processing. If the breakage of optical fibers is intended to indicate damage location [22], then only simple on/off signal recognition at the output of each fiber is necessary and the time sequencing of input optical signals through multiple input fibers may be used to reduce the overall system electronics complexity.

We have investigated the performance of the type of fiber system in Figure 5 in combination with the processor shown in Figure 6 [23]. Here, 2x2 biconical fused tapered couplers having different s-parameters are interconnected in such a way as to yield a single valued output intensity to indicate the three-dimensional location of damage. Since such processors operate as fast as the light signals can propagate through the coupler system, their use is especially attractive for structural analysis systems requiring good spatial resolution and minimal processing time.

SUMMARY

The development of quantitative NDE methods for smart skins applications involves input from a number of different technical areas. Our research group has specifically been involved in the basic analysis and development of 1) optical fiber sensors for cure monitoring, in-service lifetime structural testing, and nondestructive evaluation of gradual material degradation, 2) fiber sensor multiplexing and signal processing demanded by such systems, and 3) the integration of embedded sensors, actuators and control electronics to affect structural control systems.

Figure 5. Embedded fiber sensor array for impact analysis.
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