

LOW PROFILE OPTICAL TIME DOMAIN FIBER SENSORS  
FOR MATERIALS EVALUATION

Richard O. Claus, Sanjay Sudeora, Kent A. Murphy  
and Kimberley D. Bennett

Electrical Engineering Department  
Virginia Tech  
Blacksburg, VA 24061

ABSTRACT

Low profile in-line partially reflecting splices have been developed to allow the nondestructive internal measurement of strain in advanced composite materials. The splices consist of stripped and cleaved fiber ends spaced a few tens of microns apart and rejacketed with fiber coating material. This paper reviews the use of optical time domain methods for internal materials evaluation, the development of such splices, and their system performance.

INTRODUCTION

During the past ten years a number of potential optical fiber sensor methods have been demonstrated for the nondestructive evaluation of materials. Prototype optical fiber sensors based upon the observation of optical phase, polarization, intensity, wavelength and mode have been used to measure strain, temperature, acoustic waves, crack propagation, composite cure conditions, impact location and damage, and acoustic emission events. Currently, optical and electronic systems built to instrument most such sensors are typically customized research laboratory devices rather than commercially available units. By comparison, optical fiber time domain methods are currently advantageous because they may be implemented using off-the-shelf optical time domain reflectometers (OTDRs) developed for the nondestructive testing of optical fiber cables in communication system networks.

OTDR operation for the evaluation of optical fiber properties is straightforward although its application for materials testing becomes complicated. A simple schematic of a basic system is shown in Figure 1. Light generated by a pulsed optical source is coupled into the fiber to be examined and propagates within the fiber as one or more than one guided modes. As the light propagates along the fiber it is partially backscattered by anomalies in the waveguide structure. In otherwise unperturbed fibers, uniform Rayleigh backscatter caused by the intrinsic molecular structure of the component glasses results in an exponential decrease in received optical power as a function of time. Deviations from this anticipated baseline return signal may be interpreted as being caused by regions of local fiber perturbation, specifically local

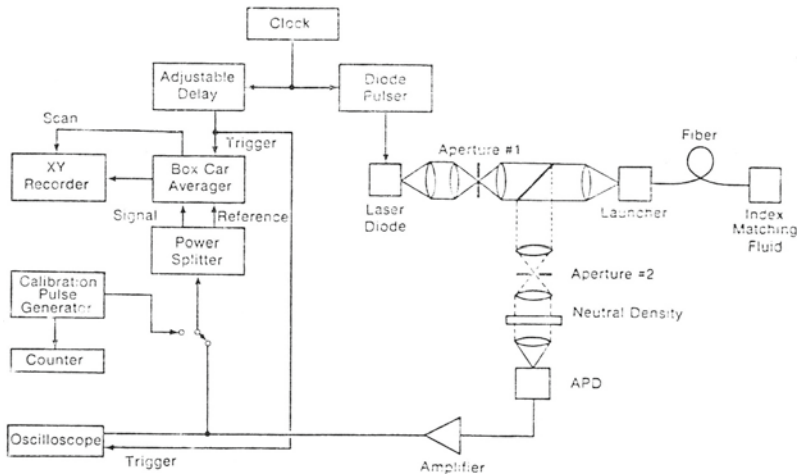


Figure 1. Block diagram of basic OTDR system.

variations in fiber geometry or index of refraction or both. The location of such regions along the length of the fiber may be determined by measuring the roundtrip time of flight of an optical pulse from the source to the backscatter location and back to the detector.

## BACKGROUND

Several research groups have investigated the possible application of OTDR, and related methods, to the nondestructive evaluation of materials (1-3), a major motivation being that in some advanced composite materials, embedded fibers may allow a convenient means for continuous internal monitoring during fabrication, normal use lifetimes, and degradation (4,6). Early work by our group used communications OTDR equipment with a spatial resolution on the order of 20 cm to locate regions of compaction pressure in multi-ply graphite-epoxy laminates (1,7). Optical fibers which were single mode and multimode at the pulsed laser source wavelength were embedded in a back-and-forth serpentine geometry between central laminae prior to cure in an attempt to provide some degree of two-dimensional spatial resolution within the flat plate test article. Output data for this type of measurement is shown in Figure 2; regions of large signal slope change correspond to locations of large applied pressure on the fiber-embedded specimen.

Several conclusions may be drawn from this work. First, mechanical loads in materials may be monitored qualitatively using relatively simple OTDR methods. Second, the spatial transient distance of multimode fibers causes the influence of backscatter at a location along the fiber length to affect the backscatter signature of locations farther along the fiber. Third, the quantitative characterization of the local mechanical conditions within the material from OTDR data is complicated by the particular nature of the fiber perturbation as well as the effective transfer of strain across the material-fiber interface (7).

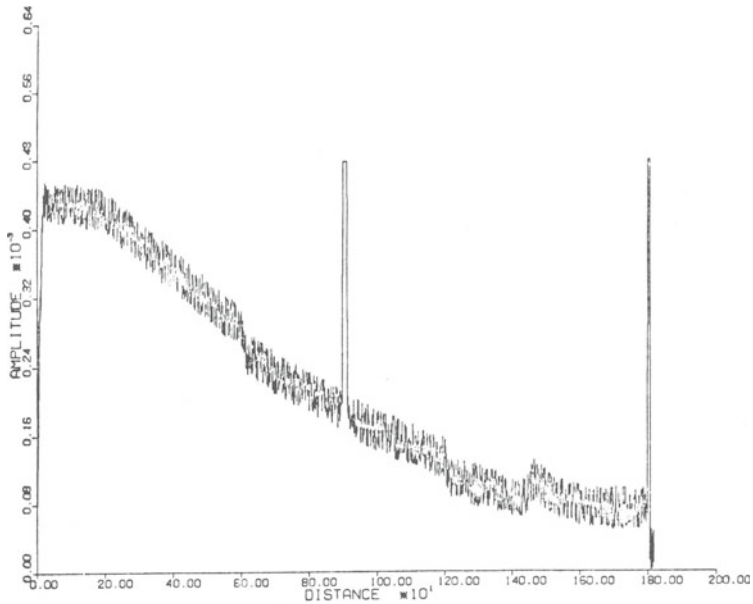


Figure 2. Backscatter signature of spliced and mechanically loaded optical fiber.

#### IN-LINE OTDR REFINEMENTS

More recent work has avoided several of these complicating factors by intentionally incorporating partially reflecting in-line splices along the length of fiber as time mark indicators as shown in Figure 3. In such a fiber a measurement of the change in the difference in the arrival times of pulses reflected back from two splices may be interpreted to yield a measure of the change in axial strain in the length of fiber separating the splices (3,8). Because time rather than intensity measurements are used to determine strain, amplitude variations caused by the interaction of successive perturbations are not important but pulse risetime and jitter become limiting factors. The performance of such a Fresnel reflection rather than backscatter-based system, limited by available electronics, is a strain resolution of 0.1 microstrain, a spatial resolution of less than 1.0mm, and the capability of interrogating approximately 50 in-line fiber sections separated by splices.

To increase the number of interrogation sites in a material, a fiber geometry such as that shown in Figure 4 may be employed (8). Here, a network of multiple sensor fibers is embedded in the material and fiber delay lines of different lengths used to provide the time separation needed to avoid the overlap of pulses from separate fibers. The embedded fibers may be arranged in several directions of course thus allowing a measure of two-dimensional strain.

If instead localized measurements of strain are desired, in-line multi-component splices such as shown in Figure 5 may be used. Here we have encapsulated a partially-reflecting fiber splice which includes an air gap between two cleaved fiber ends inside a flexible tube rather than the rigid tube used in the systems above. As the tube is strained the ends of the fibers are displaced as shown and the optical loss due to axial end separation changes. During construction of the housing the

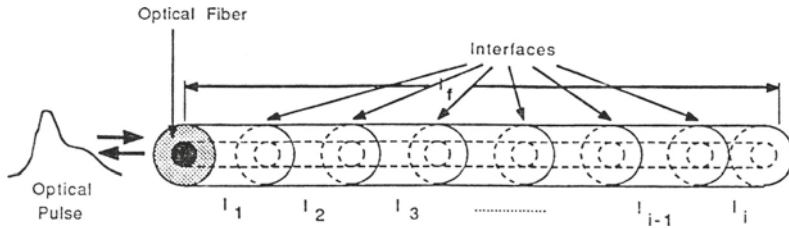


Figure 3. In-line fiber splice geometry.

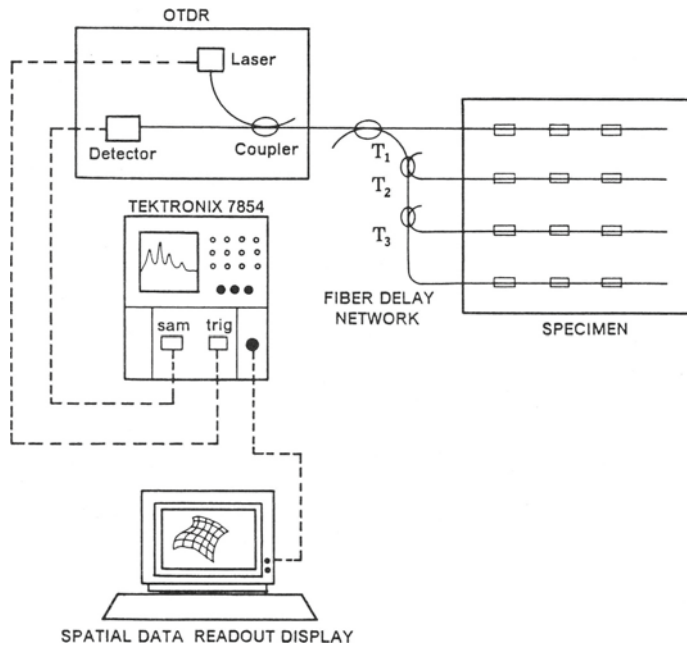


Figure 4. OTDR system for two-dimensional strain measurement.

ends of the fibers may be separated by a bias distance which allows good strain sensitivity and dynamic range (8). Analysis predicts approximately a 1.0dB change in transmitted power for a change in endface separation equal to one fiber core radius (9).

For in situ measurements in materials, however, the mechanical splice housings described above are much too large to allow embedding. To overcome this difficulty the low-profile splices shown in Figure 6 have been constructed. Jacketed multimode fiber is cut, the two ends cleaved and a short section of jacketing removed from each end. Then a single

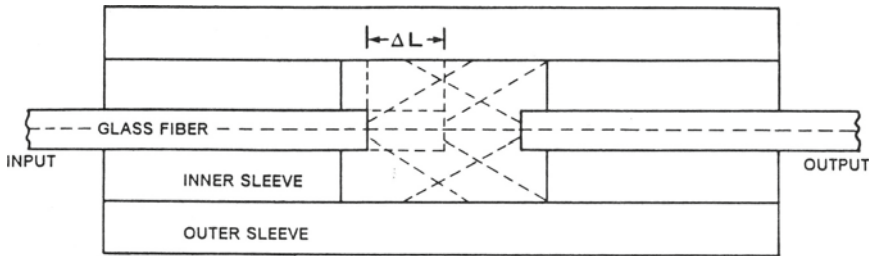


Figure 5. Flexible in-line fiber splice geometry.

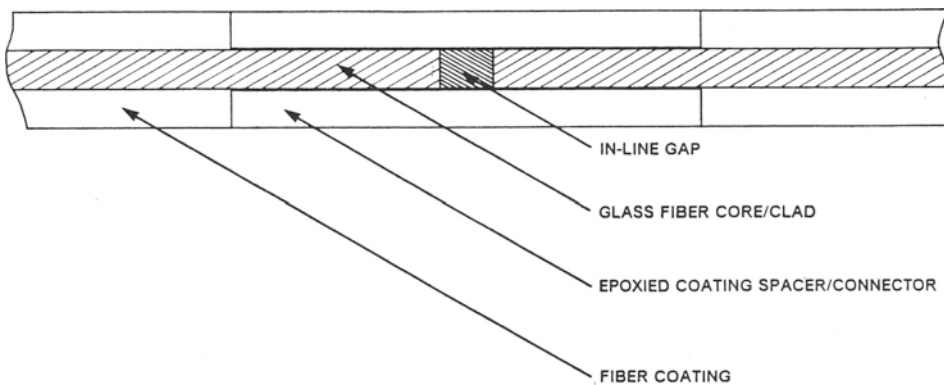


Figure 6. Low-profile in-line splice geometry.

section of jacketing tubing is replaced over the two fiber ends and epoxied at the two jacketing-to-jacketing junctions. The central section of jacketing is thus not attached to the enclosed fiber so when it is strained endface separation occurs and the local strain may be determined. For a single 50/125 multimode fiber containing such a low-profile splice with a 75 micron bias separation, the loss data shown in Figure 7 was obtained by axially loading a 0.6m length of fiber with a series of small weights.

## RESULTS

OTDR methods are currently advantageous because they can employ commercially available optics and electronics. Such systems may be arranged to interrogate distributed strain in multi-segmented structures or strain localized to the region separating two fiber ends. Low-profile fiber splice housings additionally allow the possibility of embedding in smart materials and structures rather than external attachment. System complications here include the response of the fiber to non-axial strain and the need for fast signal processing if large structures are to be evaluated quickly.

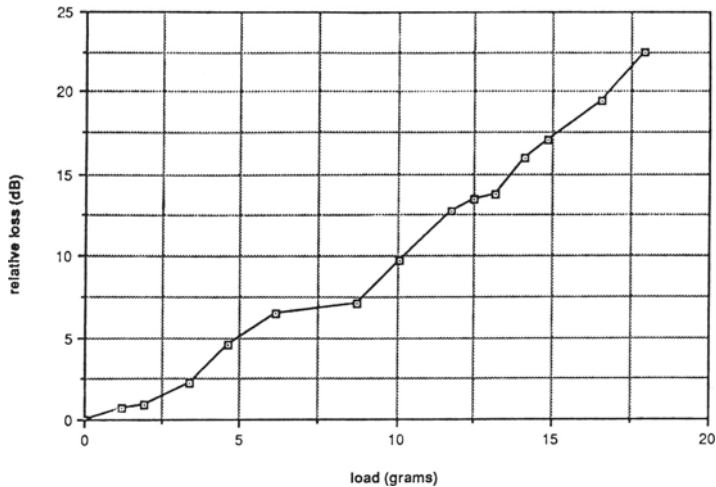


Figure 7. Loss as a function of mechanical load on in-line spliced sensor fiber.

#### ACKNOWLEDGEMENTS

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