Nontraditional Methods of Sensing Stress, Strain, and Damage in Materials and Structures

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Foreword

This publication, *Nontraditional Methods of Sensing Stress, Strain, and Damage in Materials and Structures,* contains papers presented at the symposium of the same name, held on 20 May 1996. The symposium was sponsored by ASTM Committee E-8 on Fatigue and Fracture. George F. Lucas of MTS Systems Corporation in Eden Prairie, Minnesota and David A. Stubbs of The University of Dayton in Dayton, Ohio presided as symposium chairmen and are editors of the resulting publication.

Overview

The understanding of how materials and structures behave under conditions that stress, deform, or damage them has been of concern since the dawn of engineering. Real advancement in these areas can not be achieved, however, without sensing devices that can measure accurately and repeatably, the various properties of these materials and structures. The advancement of methods that can sense basic materials properties (such as stress and strain) as well as other "damage" parameters (such as flaw density and type) are critical development of methods of designing better products for the future, whether these products better airplanes, better ground vehicles, better consumer goods, or better artificial devices for use within the human body.

This STP is intended for use of the research and development community that needs to generate and use better information of how materials and structures behave. It is intended for individuals working in areas of metals and composites, for those working in the aerospace or the biomedical areas, and for those in academic research or those in product development functions. How do we answer such questions as:

What is the stress actual distribution around a stress concentration during cyclic loading?
How can crack length measurements be made in a material or structure?
How can strain be measured on a soft tissue with enough accuracy to determine modulus?
How is bi-axial stress measured in thin tissues.
How can full-field strain measurements be made on components and complex surfaces?

This Special Technical Publication is based on the symposium on Non-traditional Methods of Sensing Stress, Strain , and Damage in Materials and Structures. This symposium was held in May of 1996 in Orlando, Florida. The symposium was preceded by two workshops on the same topic held in November of 1993 in Fort Worth Texas and in November of 1994 in Phoenix, Arizona. The Workshops and the Symposium were driven by the work of the task group E8.03.03 on Sensors which is a task group of the E8 committee on Fatigue and Fracture and it's subcommittee on Advanced Apparatus. The scope of this task group is to develop standards and encourage technology interchange concerning measurement sensors that are used in determining fatigue and fracture characteristics of materials and structures.

The advancement and development a applicable sensors is a critical part to any understanding of real materials and components design characteristics. You much be able to measure a property before you can understand it. The entire development of modern materials science and engineering has been tied to better and better sensors to measure properties. For example, the development of strain gages allowed real determination of the strain of a "spot" on a structure or materials specimen. This has allowed a much better understanding of how components and full structures, such as automobiles, airplanes and hip prostheses really behave. It has allowed for models, such as various Finite Element models, to be verified, or, to be shown where they were not correct to allow them the be modified.

Other sensors, such as modern extensometers, have allowed much more accurate measurements of local strain to be measured, and in fact, controlled. This has allowed strain controlled fatigue tests to be conducted. These tests better allow a new material's tendency for crack initiation to be understood. Other examples of sensors include eddy current devices for finding flaws below the surface, infrared devices for seeing areas where higher strains might be present, and potential drop techniques for looking a crack growth. All these methods have helped advance the understanding of how materials and structures behave.

Over the past 10 to 15 years there have also been a lot of disappointments. Various optical methods for strain measurement have been attempted with mixed success. It was expected by many, at least 15 years ago, that optical, non contacting strain measurements methods would replace contacting strain measurement techniques. We had expected that these methods would allow greater accuracy, repeatability, and be able to examine both local strains as well as full field strains. This did not happen for many reasons, and because of this the interest has declined in developing these devices. However, continual advances in computational methods, and optical technology may allow these early expectations to eventually be met.

What else may the future bring? There are many areas for potential new sensors that can significantly improve our ability to design better products. How can we measure the damage that occurs in a material or structure before it becomes apparent as a change in the stress-strain parameters or surface condition? How can we accurately "see" the full, three dimensional, micro-deformations that a component experiences. These, as well as other advances sensors, may be possible in the near future. Tremendous advances in computational capabilities may allow optical methods to show, in real time, the accurate and repeatable deformations that occur on a complex component surface. Other advances in miniaturization may allow real time sensors to be attached to areas of a structure that, in the past were in-accessible. All in all, there is a tremendous potential for future developments in sensing technology related to work in fatigue and damage of materials and structures.

The Special Technical Publication is organized into four sections, each encompassing papers of similar interest. The first, Nontraditional Extensometers, is for novel methods of measuring point to point deformation, or when normalized, strain. Dave Walrath et al explains a technique of using an optical fiber based sensor in lieu of a normal strain gage sensor. This device is not effected by any ambient electrical or magnetic field. William Sharpe et al discusses the development of interferometric displacement gages, which can be used for very point to point measurement at very small scales, such as at the root of a crack. Nigel Shrive et al, expounds upon a novel arrangement for a contacting extensometer. This device is able to minimize contact loads to one gram, allowing direct strain measurement of difficult materials, such as thin wire or biological tissues.

The second section, Nontraditional Crack Measurement Techniques, goes through methods for measuring crack length, expect for the last paper by Haggag. Haggag's paper goes through a technique of measuring the stress-strain and "damage" parameters of the material as part of a structure in situ. As such it is useful in determining the useful life left in a component.

Varvani-Farahani goes through a method of determining, utilizing a confocal scanning laser microscope, the morphology of a crack, as well as it's crack length. This is a case where more information than is traditionally is made available. The paper by Tiku et al goes through an new potential difference technique for crack length determination that utilizes current focusing. This allows the technique to be used with large structural applications, where traditional PD methods were limited to certain specimen geometries. Nahm et al goes through an interesting method of measuring surface cracks from a remote location utilizing a CCD array with controllers, software, and a 3-D translation system. This allows crack measurement to be made on specimens at high temperature or under other adverse conditions, as long as a clean optical path to the specimen exists.

The third section, Optical, Non-Contacting Strain Measurement Devices, has four excellent papers on optical methods of measuring both point to point and full field strains. Seida et al describes a method of adapting current machine vision technology to strain measurement by tracking the positions of features on the surface of a specimen. Rand and Grant examine a method of measuring the planar Biaxial strains in a thin film polymer. Their method uses a random speckle pattern and a CCD camera. Cardenas-Garcia analyses the grid technique as a general method of measuring biaxial stain on a simple or complex surface. Chaing et al go though a examination of full field speckle photography as a method of measuring strain. This paper is especially interesting as it goes looks at very small scale full field strain measurements.

The last section, Ultrasonic and Infrared Techniques, some new and promising techniques are described. These methods do not relay on surface features, so are able to "see" below the surface of a specimen or component. Buchanan et al describes a technique to measure the damage within ceramic matrix composites (CMC) and metal matrix composites (MMC). They utilize bulk and surface ultrasonic waves to characterize the material in situ while undergoing mechanical simulation. Wang depicts an ultrasonic method to measure the damage caused by radiation in a reactor steel.

Welch et al and Lesniak et al both describe different aspects of new commercial method for thermoelastic stress measurement. This method is able to quickly analyze measure the reversing stresses caused by temperature variations. Their method is a evolution of the older SPATE systems. Finally, Hyodo et al describe a similar method that measures the stresses in a biological specimen, the human tibia.

In summery, there are a great many different emerging techniques to measure various parameters in materials and structures. Be cautioned that most of these methods are still in the development stage. Exceptions to this include the above mentioned thermoelastic system, the extensometer described by Shrive, and the system described by Haggag. Some of the others will become developed further into commercial devices, others may not.

This symposium certainly shows that the community is potentially on the verge of a whole host of new sensing tools that may allow us to learn more about the materials and structures that we can make the products of future from.

The symposium cochairmen would like to acknowledge the efforts of several individuals, in addition to the individual reviewers, that made this STP possible. George Hartmann, of UDRI, made many valuable suggestions in the planning process, as well as chairing one of the workshops. Art Braun, chairman of subcommittee E8.03 and Joe Gallagher, chairman of E8, both were instrumental in encouraging this symposium and STP to exist. Finally, Shannon Wainwright of the ASTM Staff, did a tremendous job of keeping it all together. Her endless encouragement and gentle nudging made it a pleasure to be involved with ASTM in editing this STP.

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Contents

ULTRASONIC AND INFRARED TECHNIQUES

Nontraditional Extensometers

Guy M. Houser,[1] and David E. Walrath [2]

USE OF AN OPTIC LEVER AS A SHORT GAGE LENGTH EXTENSOMETER

REFERENCE: Houser, G. M. and Walrath, D. E., "**Use of an Optic Lever as a Short Gage Length Extensometer,**" Nontraditional Methods of Sensing Stress, Strain, and Damage in Materials and Structures, ASTM STP 1318, George F. Lucas and David A. Stubbs, Eds., American Society for Testing and Materials, 1997.

ABSTRACT: A short gage length extensometer, based on the principle of an optic lever, was designed and tested as a medium resolution, short gage-length displacement transducer. The goal was to develop a short gage-length extensometer as a potential replacement for foil resistance strain gages. The optic lever used step-index optical fibers to modulate reflected light as a function of target displacement. This provides the basis for a responsive displacement (strain) transducer that is small in size, insensitive to electrical noise, and resistant to elevated temperature and radiation levels. Transducer design was facilitated through use of an analytical model to predict performance. A prototype transducer was tested and compared to foil resistance strain gage results. The prototype demonstrated 25 microstrain resolution over a 10% strain range.

KEYWORDS: fiber optic, strain measurement, optic lever

Foil resistance strain gages have been used to measure strain for many years. They have excellent strain measurement resolution and can be made to small size, thus measuring average strain on a small area. Foil resistance strain gages are a low cost alternative to a variety of strain measuring systems. Foil resistance strain gages require careful installation, and can not be removed and reused. In materials testing, where specimens are typically destructively tested, the time and expense of mounting strain gages on each test specimen can become significant, making reusable transducers desirable.

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One such strain transducer design is an extensometer, an adaptation of the foil resistance strain gage. The extensometer consists of foil resistance strain gages mounted on a c-shaped or curved beam. As the ends of the beam are displaced (extended), the beam is subjected to bending, producing strain which is detected by the strain gages. The extensometer is calibrated to measure displacement ΔL, from which the strain ε is computed by dividing by the gage length L, the original distance between the ends of the c-shaped beam. That is,

$$\varepsilon = \frac{\Delta L}{L}.$$

The extensometer measures average strain in a specimen through the region encompassed by the gage length. Strain resolution of an extensometer is enhanced by using longer gage lengths. Typical gage lengths for commercial extensometers range upward from 12.5 mm. These longer gage lengths are typically not a problem in materials testing where uniform strain (stress) fields are produced in the test specimens. Shorter gage length extensometers are more difficult to mechanically attach to a specimen, and have poorer strain resolution.

The desired strain transducer for materials testing would be one with a strain resolution of 10^{-5} over a gage length typical of common foil resistance strain gages, say 3-4 mm, while being easily installed and reusable. The objective of the work described in this paper was to develop such a device, based on use of a fiber optic lever [1].

FIBER OPTIC LEVER

The fiber optic lever was described by Frank in 1966, [2] and Kissinger in 1967 [3]. A quantitative description of the principles governing fiber optic levers was presented by Cook and Hamm in 1979 [4]. The fiber optic lever, shown in Figure 1, is a

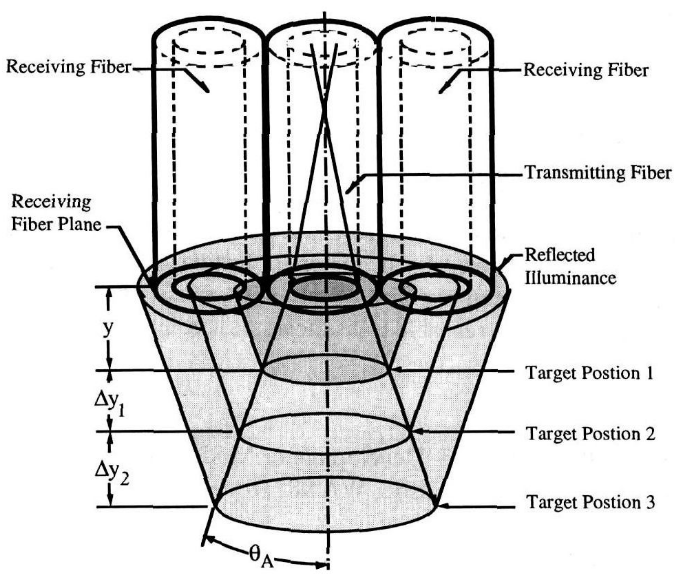

Figure 1. Operating Principle of the Fiber Optic Lever.

device that is capable of modulating the reflected power from a translating target in such a manner that it is a function of the target displacement. The basis of operation is that light is transmitted through a step index optical fiber to illuminate a reflective target. Light exits the transmitting fiber as a diverging cone. The light cone is incident on a reflective target that translates parallel to the fiber bundle longitudinal axis, or perpendicular to the ends of the fibers. Translation of the target modifies the amount of reflected illuminance incident on receiving fibers surrounding the transmitting fiber. Part of the reflected illumination is transmitted by receiving fibers to a photodetector. The output of the photodetector is a function of target displacement. A conceptual fiber optic lever based displacement measurement system is shown in Figure 2.

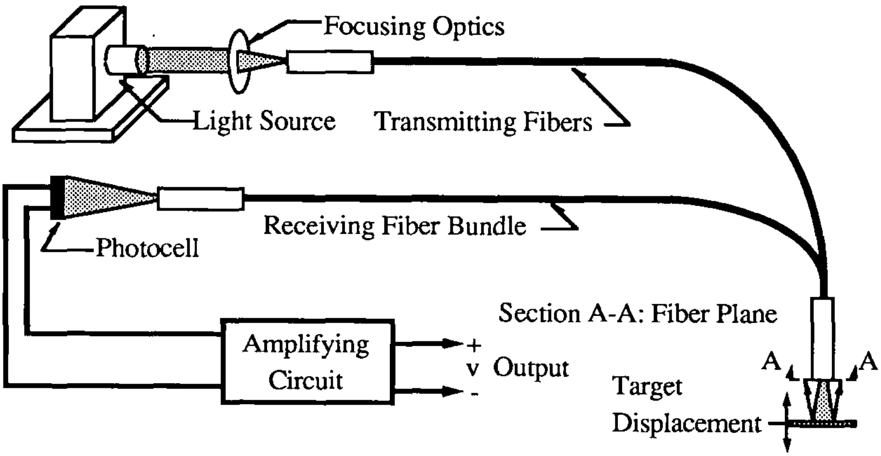

Figure 2. Conceptual Model of a Fiber Optic Lever Displacement Measurement System.

The fiber optic lever displacement transducer is a low cost device that is insensitive to electrical noise. Original applications employed the device as a responsive, small displacement sensor for use in vibration measurements. Sciences ranging from biomechanics to automated manufacturing have since utilized the fiber optic lever for commercial use, see for example [5,6].

SEVEN FIBER OPTIC LEVER MODEL

A mathematical model for calculating the illuminated receiving fiber area was greatly simplified by assuming that electroluminescent energy is coupled into lossless, nondispersing ideal step index fibers. It was further assumed that the reflective target translates in a direction parallel to the longitudinal fiber axis [4]. Extending this analysis to a seven fiber model, from the target vantage point one would view the reflected illuminance area on the fiber plane as shown in Figure 3. The illuminated fiber area of a single fiber can be multiplied by the number of receiving fibers to compute the total illuminated fiber area.

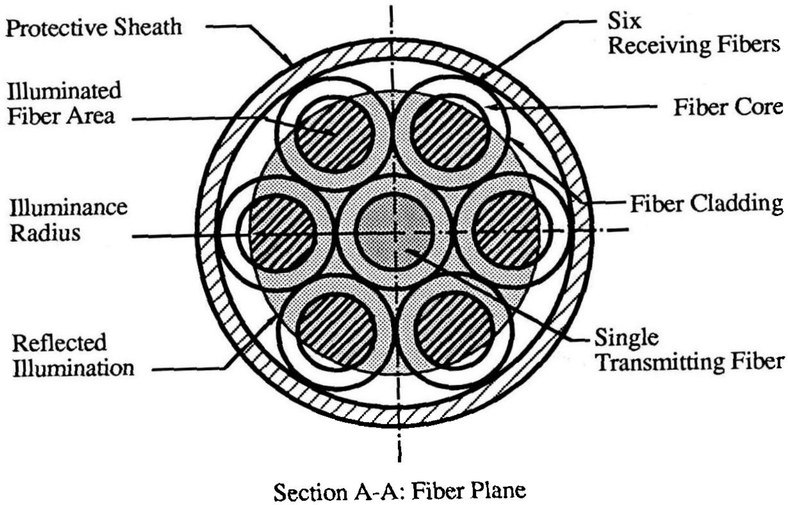

Figure 3. Illuminated Receiving Fiber Core Area Due to Reflected Illuminance on the Fiber Plane for a Seven-Fiber Optic Lever.

Figure 4 shows a cutaway view of the 3 middle fibers. The triangle (abd) shows

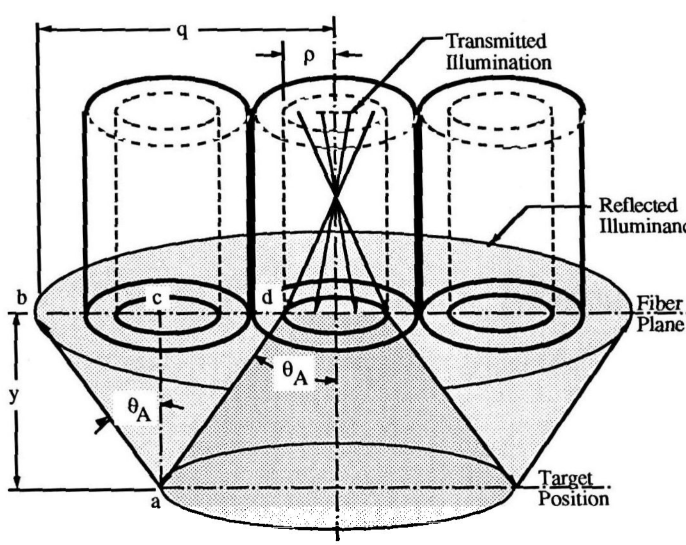

Figure 4. Reflected Illuminance Radius at the Fiber Plane

that the reflected illuminance area radius q minus the transmitting fiber core radius ρ is twice the target distance y times the tangent of the fiber acceptance angle θ_A. The reflected illuminance area radius is

$$q = (2\ y \tan \theta_A) + \rho.$$

The illuminated receiving fiber area for a single fiber is the intersection of areas defined by the reflected illuminance and the receiving fiber core, as shown in Figure 5. The area of

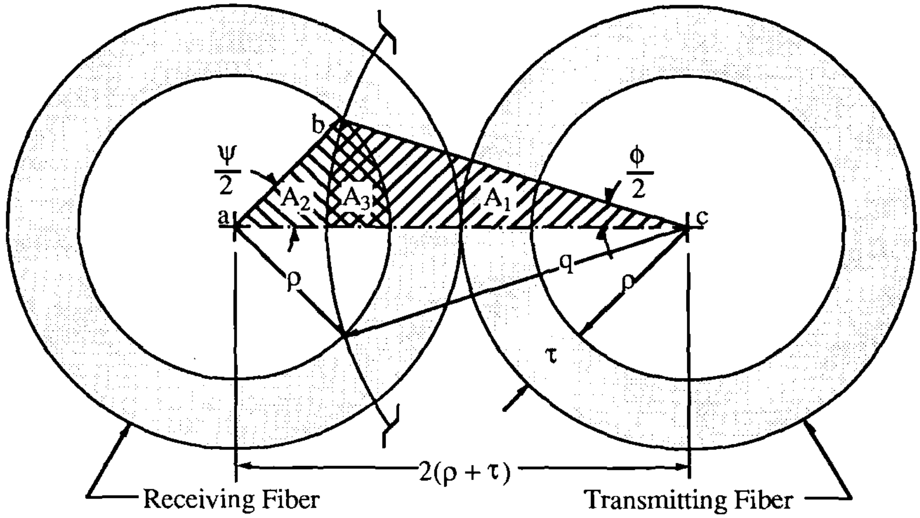

Figure 5. Illuminated Receiving Fiber Area ($\psi/2 < \pi/2$)

the arc swept by the illuminance radius, an angle $\Phi/2$ (∠bca), is A_1, and by the fiber core radius, an angle $\psi/2$ (∠bac), is A_2. The area A_3 is the intersection of A_1 and A_2 and the subtraction of excess triangular area (abc). Thus

$$A_3 = A_1 \cap A_2 = \frac{q^2}{2}\left(\frac{\Phi}{2}\right) + \frac{\rho^2}{2}\left[\left(\frac{\Psi}{2}\right) - x_0 \sin\left(\frac{\Phi}{2}\right)\right]$$

where x_0 is related to the fiber center spacing as

$$x_0 = \frac{2(\rho + \tau)}{\rho}$$

where τ is the cladding thickness. By relating $\Psi/2$ and $\phi/2$ as,

$$\frac{\Psi}{2} = \sin^{-1}\left(\frac{q}{\rho}\sin\frac{\phi}{2}\right)$$

defining the reflected illuminance ratio such that