OTC 14242

Direct Measurement of Large Strains in Synthetic Fiber Mooring Ropes Using Polymeric Optical Fibers

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This paper was prepared for presentation at the 2002 Offshore Technology Conference held in Houston, Texas U.S.A., 6–9 May 2002.

Abstract

Synthetic Fiber Mooring Rope constructed from high performance polyester is an important emerging technology which promises to advance the economical production of oil and gas from deepwater reservoirs in the Gulf of Mexico (GOM) and elsewhere around the world. Considerable effort has been focused in recent years to develop the technology and confidence to apply synthetic fiber rope technology in a relatively new application in which the material is expected to carry load for decades in the marine environment. Synthetic fiber mooring ropes have been deployed successfully in Brazil and have seen limited service in the Gulf of Mexico. Light-weight synthetic fiber mooring ropes have high strength and adequate stiffness, but are much more susceptible to damage than their steel counterpart. Close monitoring of their performance is, therefore, a necessary requirement to insure their continued safety and reliability. The current paper discusses ongoing research activity to explore the feasibility of using polymeric optical fibers to measure directly large axial strain in long lengths of mooring rope. The strains measured in polymeric optical fibers exhibit good one-to-one correlation with applied strains within the test range studied (10% or less, typically). Additional efforts are in progress to assess other factors including the effects of the environment, creep, and cyclic loading, and measurement of the response of polymeric optical fibers integrated into the body of a synthetic fiber mooring rope. Measurement of the accumulated strain in the rope at any point in time could provide a reliable benchmark with which to estimate the remaining mooring rope life and help establish criteria for rope re-certification or retirement. Future safe deployment of the synthetic fiber moorings will be significantly enhanced if a reliable technique can be developed to monitor their performance insitu in service.

Introduction

Rope technology in which readily available organic fiber material is spun and twisted to form a rope was developed several millennia ago. The Persians were able to spin huge ropes two feet in circumference and a mile long to build an invasion bridge across the Hellespont to Greece[1]. Modern synthetic fiber rope began with the development of nylon in 1938 followed later with the introduction of other fibers such as polyester. In the last two decades, with the discovery of large oil deposits in deepwater offshore reservoirs, a special application for synthetic fibers has developed as mooring rope for offshore platforms.

The traditional mooring rope system uses a catenary steel chain or rope in which the restoring force for station keeping is developed by the weight of the steel mooring. The weight of the steel lines in water must, of course, be supported by the buoyancy of the platform. As the water depth increases, weight becomes a serious platform design issue and light-weight synthetic fiber mooring ropes have gained considerable attention as an alternative system. Alternative systems for positioning floating platforms are shown in Figure 1. Petrobras has used polyester mooring ropes for all their recent moored platforms[2] and two MODU drilling rigs were recently given approval to use polyester moorings in Gulf of Mexico operations[3]. The structural concept for synthetic fiber moorings is not a catenary, but a taut leg system in which the polyester rope is deployed from the platform at approximately 45-degrees from vertical and placed under tension (Fig. 2). The advantages of the polyester taut leg mooring are huge weight savings, a more efficient system allowing a smaller footprint on the ocean floor and a favorable force vector to restore the platform to its neutral position, and lower cost.

Rope Integrity and Damage Assessment

A review of design considerations for polyester rope moorings is presented in Reference 4. American Petroleum Institute recommended practice guidelines for synthetic fiber mooring ropes is available in Reference 5. The Minerals Management Service has sponsored research[6] and encouraged the industry to develop better understanding of the effects of damage to synthetic fiber mooring ropes expecting the outcome to result in damage tolerance guidelines. A review of the damage which can be experienced in synthetic fiber mooring ropes is presented in Reference 7. Much of the potential for damage occurs as a consequence of mishandling during the initial installation phase in which the ropes can be cut, crushed, kinked, or otherwise damaged. They can also experience internal and external wear due to friction and abrasion during the long service life. Petrobras experience indicates it is important to avoid contact with the sea bed[2]. Ingress of mud or sand is a threat to the integrity of mooring ropes which may, in combination with cyclic loading, affect the strength of the rope. Some rope manufacturers are now integrating particle filters into the outer cover of the rope to address this concern. Future safe deployment of synthetic fiber mooring ropes would be significantly enhanced if a reliable technique can be developed to monitor the performance of the rope in service. Needed is a reliable non-destructive technique that can be used to monitor the overall performance of the rope and provide a warning of the loss of integrity of the rope.

Guidelines established by the American Bureau of Shipping for like-new condition rope recommends that the maximum tension in a line, including dynamic effects, not exceed 55% of the minimum breaking strength[8]. In addition, maximum tension for damaged rope should not exceed 70% of the minimum breaking strength. Additional safety factors are being recommended by some designers to account for current uncertainties in performance including creep[4]. The ultimate strain capability for polyester mooring rope, including the kinematic response due to the twisted and braided architecture of the rope and stretch in response to load, is on the order of 15 percent. The literature suggests that the accumulative strain at failure of polyester rope, within a narrow range, is almost a constant independent of load path or load history. Reference 9 states "The tensile fatigue behavior of nylon and polyester single fibers and yarn is characterized as a simple process of accumulation of creep strain and failure occurs at a strain that is similar to the static strain to failure". If the accumulative strain in the rope could be measured, one would have a reliable structural health monitoring method for this critical primary structure. Measurement of the state of strain in the rope including accumulated strain should provide; therefore, a reliable benchmark with which to estimate the remaining life of the rope and allow the establishment of meaningful criteria for rope recertification or retirement. Such measurements would be particularly useful following installation and hurricanes or other major disturbances.

Optical Fiber OTDR Strain Monitoring Method

No satisfactory method for assessing the performance of Synthetic Fiber Mooring Rope during a long life-time of service exists today. The current method to monitor the performance of synthetic fiber mooring ropes in service includes measurement of load and gross measurement of the stretch of the mooring line or visual inspection with an ROV. Monitoring the strain with glass optical fibers was considered in the current study, but the allowable strain in glass fibers is less than 2 percent and therefore inadequate for *direct measurement* of the strain in the rope fiber strands. An EC funded consortium in the U.K. recently announced a rope strain monitoring method based on glass optical fibers, but according to available literature, the strain in the glass fiber is limited to "only a small portion of the longitudinal rope strain"[10]. The technique appears to indirectly measure the longitudinal strain experienced by the rope, probably by winding the optical glass fiber in a large helical angle and measuring the strain through calibration or analysis.

Highly elastic polymeric optical fibers can potentially record tensile strains of 10 percent or more, making them attractive as sensors to directly measure the axial strain response of the rope. Bragg diffraction grating technology is one commonly used method to measure strain using optical fibers; however, the method being studied in the current investigation is to measure changes in the length of long discrete segments of the polymeric optical fiber using optical time-domain reflectometry (OTDR).

The OTDR technique is an adaptation of a method used by the telecommunications industry to accurately locate splices, losses and breaks in fiber optic cables over long distances. An OTDR measures spatial positions along an optical fiber by launching brief pulses of light into one end of the fiber and then detecting the subsequent reflections at physical interfaces discretely inserted at selected location along the fiber (Fig. 3). By measuring the transit time of the reflected pulses and by knowing the speed at which light travels in the optical fiber, a very accurate measure of the distance to each reflective interface can be attained. If a gauge section undergoes a strain, hence changes in the interface's spatial position along the fiber, one can measure strain by measuring the change in position. An OTDR with a picosecond pulsed light source can measure distances with an accuracy of about 0.4 inches, yielding strain measurements of 0.1% over a 33 foot gauge length segment. It is anticipated that polymeric optical fibers can be used to make 10 to 30 strain measurements along a 1,000 foot mooring rope by spacing the interfaces at 33 to 100 foot intervals. A unique optical fiber coupling method is being used to insert the reflective interfaces along the length of the polymeric optical fiber, and customized software algorithms are used to measure strain between adjacent reflective interfaces. With multiplexing it should be possible to monitor several mooring ropes in rapid sequence. Such measurements would then be compared with pre-established design guidelines and remedial action taken, if necessary.

The basic principles of using glass optical fibers are well established within the communication industry applications. Although polymeric fibers have been developed and studied for the communications industry, they have been of less interest because they exhibit higher attenuation than glass optical fibers and lack the need for high strain capability.

Optical fibers used in communications, of course, must travel great distances; whereas, the distance needed for the mooring rope application is orders of magnitude shorter. On the other hand, the loss of signal in a polymeric fiber is a definite challenge. To overcome this limitation, the current investigation is studying several candidate polymeric fibers and developing methods to achieve a high strength signal through amplification, optimum selection of laser signal wavelength, reflection parameters, and collection and amplification of the reflected signal.

Polymeric Optical Fibers

The introduction of polymeric (plastic) optical fiber actually preceded the introduction of glass optical fiber. The DuPont Corporation first developed polymeric fibers for illumination engineering applications in the late 1960's. Thirty years later there is continued, albeit re-focused, commercial interest in polymeric optical fiber as a viable data carrier in special installations with data transmission rates of 300 megabit/s to 3 gigabit/s. Polymeric optical fiber is "faster" than copper wire and is therefore attractive for Ethernet and multimedia applications. In the present application the large bandwidth is a minor advantage.

The most important attribute of polymeric optical fiber is its ability to stretch and relax when subjected to cycles of large tensile strains. Within the elastic deformation limit, polymeric fibers have a nearly linear response to applied tensile strain. The major disadvantage of polymeric fiber, when compared to conventional glass fiber, is its significantly larger optical attenuation per unit length. The attenuation of polymeric optical fibers is 10 to 1000 times greater than that of glass at common communication wavelengths. However, the mooring rope applications does not require extreme long data haul distances like telecommunications. With clever design parameters, the attenuation should be manageable to allow the strain from relatively long length rope segments to be measured..

Most commercially available polymeric optical fibers are formulated from polymethyl methacrylate, a transparent plastic. Two commercially available formulations of this type of fiber were tested. In addition, a novel fiber made from a perfluorocarbon-based polymer was studied..

Guidelines for Monitoring Mooring Rope Strain

An optical fiber strain monitoring system must be integrated into the structure during the design and manufacturing phase and guidelines need to be established to interpret how to respond to the data generated. As noted above, rope performance may be degraded by installation damage and by property changes which occur during a long life-time of service. Although the OTDR technique requires active electrical and optical signal generating equipment, it does not need to continuously monitor the strain in order to determine the accumulated strain. The system measures the length and change in length of discrete predetermined segments of the optical fiber integral to the rope. The system, however, should actively operate during a storm to capture maximum strain excursions. Creep, a property characteristic of synthetic fiber materials, will also accumulate in the optical fiber if the optical fiber integration is able to impose the same strain on the fiber as on the rope.

The location of the optical fiber in the mooring rope is part of the design challenge. A rope under load exerts lateral force and creates friction between adjacent fibers. The interior of the rope experiences higher lateral force and friction than fibers near the surface of the rope. Positioning the optical fiber in elements near the center of the rope protects the optical fiber and should impose the restrain to keep it from slipping. One rope configuration under study composed of paralled laid subropes is shown in Figure 4 . Each subrope has five elements, four larger twisted elements surrounding a smaller axially oriented central element as shown in Figure 5. Inside the smaller center element, oriented parallel to the axis of the rope, is an ideal location for a polymeric optical fiber to directly measure the stretch of the rope. Positioning of optical fibers in the twisted strands will also be investigated. The study is also investigating if there is sufficient restraining force to cause the optical fiber to experience local strain anomalies such as would occur due to local damage. If local strain anomalies can be measured, the technique will be a valuable method for warning of damge and even providing the precise location of damage.

Requirements for monitoring strain in synthetic fiber mooring ropes are still being formulated. Initial guidelines are summarized by the following:

- Strain measurements up to 10 percent
- 0.1% strain resolution
- Measurement in each discrete 30 ft. gauge length segment along the rope length
- Integration of a single optical fiber into a rope at least 1,000 ft. long.

"Stretch" targets include 0.5 % resolution in 5 foot gauge lengths and measurements up to 15 % strain in 2,500 foot rope lengths. With multiplexing, it will be possible using the same OTDR instrumentation to have more than one polymeric optical fiber in a rope or to measure strain is several ropes. The development is driven by the objective to develop a monitoring system which is practical for deployment on offshore platforms. The program is also following closely the damage tolerance program currently being conducted for the MMS[6].

Experimental Results For Polymeric Optical Fibers

The first experimental task in the development of the mooring rope strain sensor is to measure the response of candidate polymeric optical fibers to strains of the magnitude expected to occur on deployed ropes. To this end three candidate polymeric optical fibers were selected for laboratory tests. The three polymeric optical fibers designated A, B, and C are commercially available as a 0.5-mm-diameter buffered fiber configuration. Table 1 summarizes some of the distinguishing material characteristics. The actual values of the refractive indices at the OTDR output wavelength (850-nm) were not known at the time of the measurements; therefore, the refractive index was estimated using on available core material information. To calculate a more accurate value for the applied strain from the optical fiber measurement, a precise value of the refractive index must be determined. For evaluating the performance of the fibers in this initial task, the estimated value was considered sufficient.

Table 1.- Polymeric Optical Fiber Properties.

Fiber Formulation	Attenuation at 850 nm (dB/meter)	Approximate Core Diameter (micrometers)	Refractive Index (estimated)
A – Polymethyl methacrylate	2	250	1.49
B – Polymethyl methacrylate	2	250	1.49
C - Perflourocarbon	0.03	125	1.30

A photograph of the test apparatus used to deform the fiber and measure the mechanical and optical strain is presented in Figure 6. For each measurement, two meters of fiber were cut from the supply spool, both fiber ends were polished for optimum transmission capability, and a 100-cm-long segment of the fiber was clamped between two movable stages. The movement of the clamped ends provided the applied strain in the 100-cm-long gauge length. One end of the fiber was then coupled to a glass fiber that was connected to the output of an Optoelectronics OFM20 high-resolution OTDR. The OTDR operates with an 850-nm wavelength source and is capable of 1-mm spatial resolution at arbitrary distances along fibers with lengths up to a few kilometers. The motion of one of the moveable stages was controlled with a linear stepper motor with a resolution of 1 micrometer. Using this technique it was possible to apply strains to a resolution of about 0.001% in the range 0 to 10%.

Figure 7 shows a typical strain response of Fiber A. The maximum applied strain was 4%, well within the elastic limit of the fiber. The uncalibrated OTDR measurements are plotted as a function of the applied strain, and the line is a linear least-squares fit to the OTDR measurements. The good fit indicates the strain is linear.

Figure 8 shows a typical strain response of Fiber B. The maximum applied strain was 5%, and the uncalibrated OTDR measurements are plotted as a function of the applied strain. Once again the measured strain is very linear with applied strain and the OTDR measurements are in very close agreement with the applied strain values.

Figure 9 shows a typical strain response of Fiber C. The maximum applied strain in this measurement is almost 8%. This strain value may be approaching the boundary of the elastic deformation limits of the fiber because there is a slight departure from linear response above 7% strain. The fiber relaxation upon reversal of the applied strain was measurably slower than when a smaller maximum strain was applied.

All three fibers exhibit acceptable strain response and reproducibility within their elastic limits. Additional measurements to test the performance near the end of the elastic regime and into the plastic deformation regime are underway in the ongoing investigation.

Discussion

An exploratory study is being conducted to evaluate the potential of polymeric optical fibers to measure directly the large strains typically experienced by synthetic fiber mooring ropes used on offshore floating oil platforms. In the first phase reported herein, the ability to accurately measure the strain in three commercially available polymeric optical fibers was measured using optical time domain reflectrometry technology. Initial benchtop measurements show all three optical fibers to exhibit a linear response to large applied strains. With more precise calibration, all three optical fibers should provide good one-to-one correspondence between applied and measured strain values. The dramatically better transmission of fiber formulation C (low attenuation) makes this fiber a leading candidate for the mooring rope application. With proper integration, instrumentation and technique, polymeric optical fibers appear to offer high potential to measure large strains on long length mooring rope segments.

This program was initiated in the second half of 2001 and much additional study remains to be conducted. Polymeric optical fibers will be integrated into the body of selected mooring rope designs and tension tests conducted to validate the correlation between mechanical and optical measured strains. Future work includes addressing critical issues for the performance of the polymeric optical fiber in the mooring rope application including application of even larger strains, study of the effects of cyclic loading and creep, and environmental effects including sea water and high hydrostatic pressure exposure.

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Acknowledgements

The authors wish to express appreciation to Shell International Exploration and Production Inc., Whitehill Manufacturing Corporation and Puget Sound Rope for their guidance and support. This research was sponsored by the U. S. Department of Energy under Contract No. DE-AC05-00OR22725 with the Oak Ridge National Laboratory, managed by UT-Battelle, LLC.

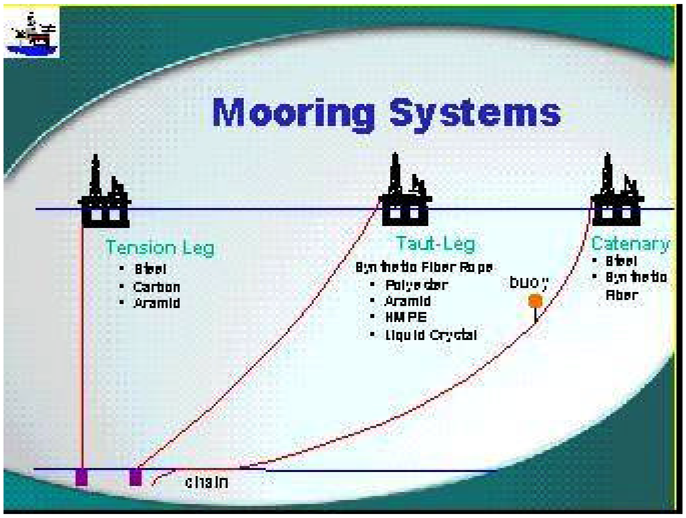

Figure 1.- Floating platform mooring systems.

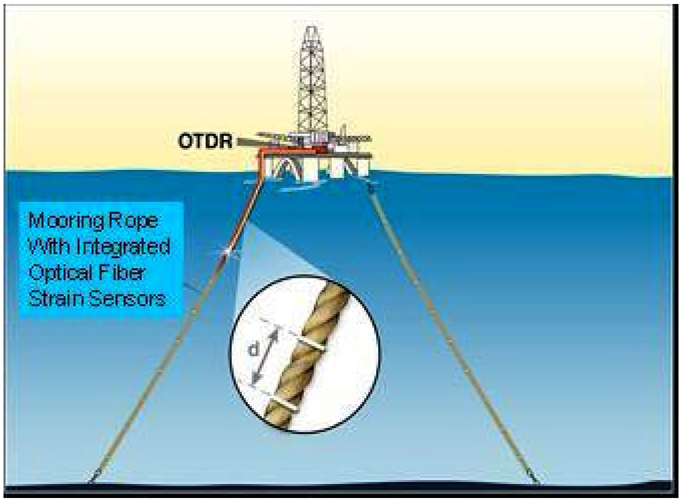

Figure 2.- Taut leg moored platform using synthetic fiber moorings connected to steel chains at the sea bed and platform.

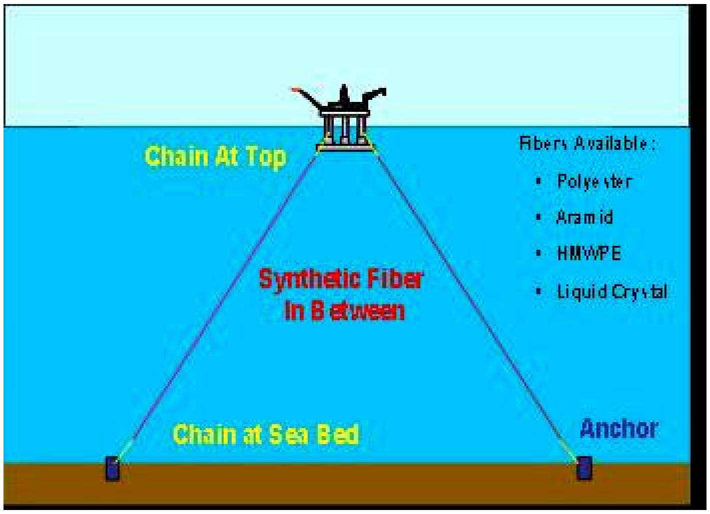

Figure 3.- Sketch showing polymeric optical fiber strain monitoring system integrated into mooring lines of taut leg moored floating platform. Multiplexing to allow multiple lines to be monitored.

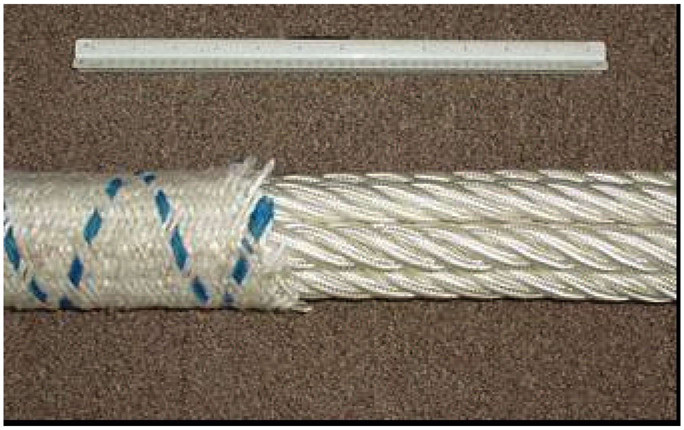

Figure 4.- Mooring rope constructed of seven subropes and encapsulated in a braided outer cover. (Manufactured by Whithill Manufacturing Company)

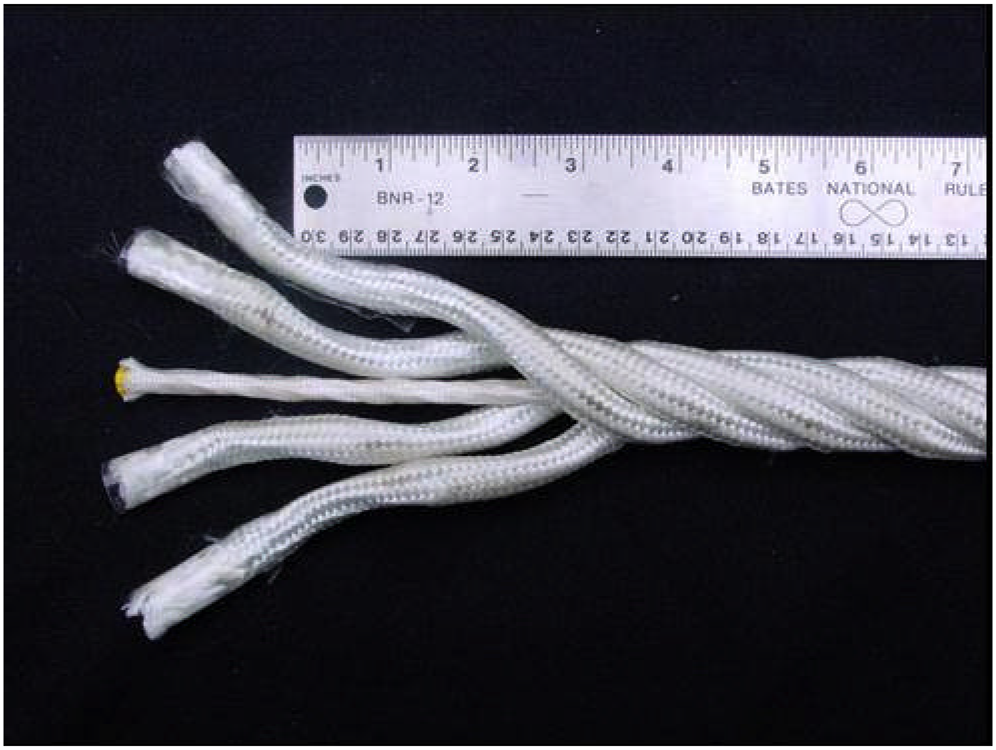

Figure 5.- Proposed location for polymeric optical fiber in small center core and twisted elements of subrope of mooring rope shown in Figure 4.

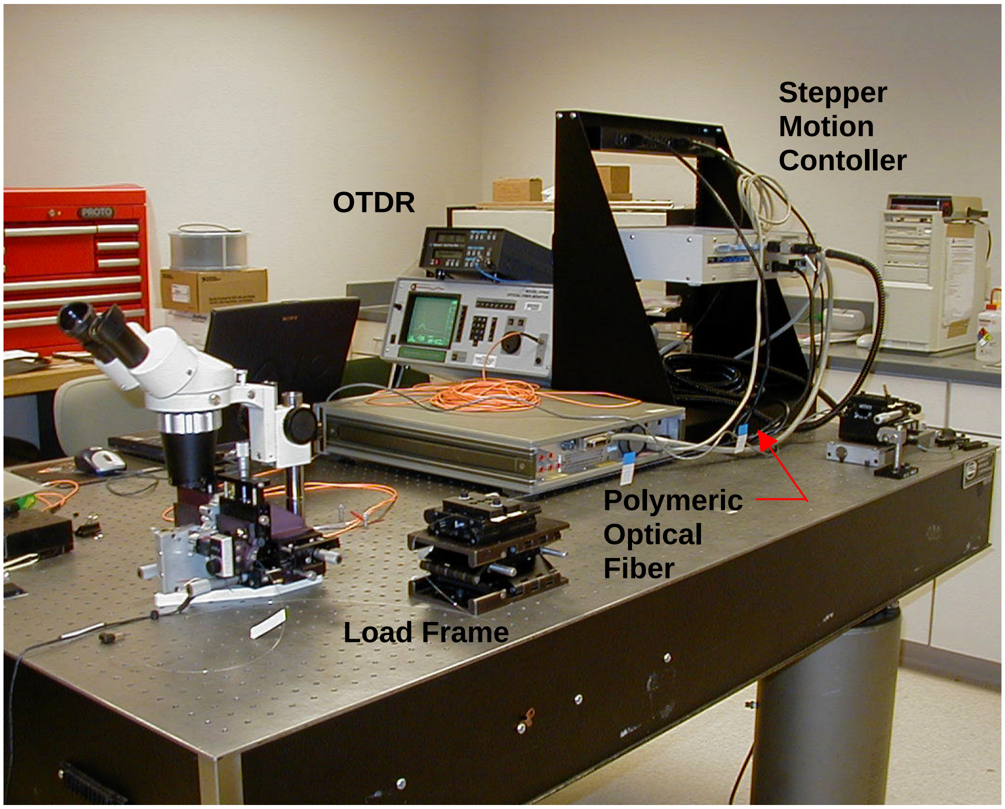

Figure 6.- Photograph of tensile strain apparatus. Short gauge lengths of about 1 meter of polymeric optical fiber samples are clamped between moveable stages, and the fiber length is measured optically by the OTDR as the fiber is subjected to strain cycles. The fiber is faintly visible in the foregoing, just above the table, with pieces of tape affixed to it for visualization.

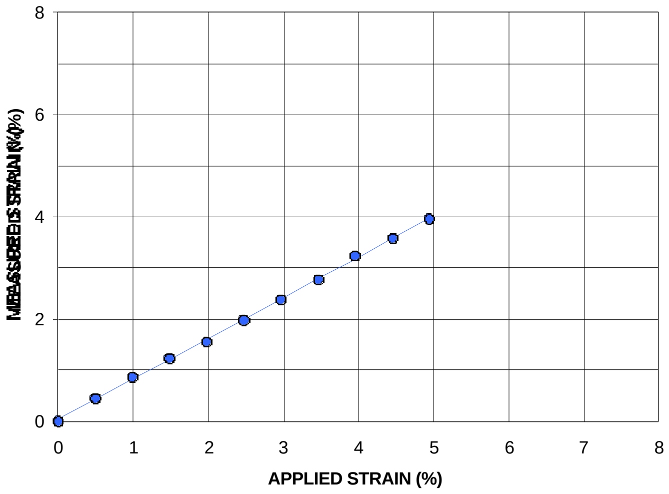

Figure 7. Typical strain response of polymeric optical fiber type A. Circles, OTDR measurements of fiber elongation under longitudinal strain; line, linear least-squares fit to strain measurements.

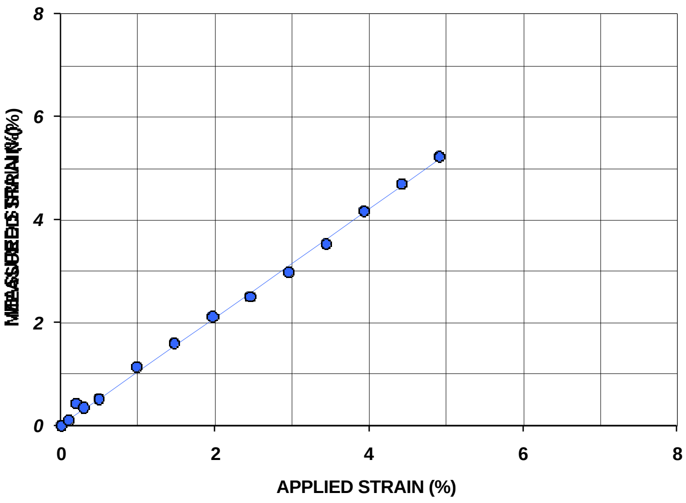

Figure 8. Typical strain response of polymeric optical measurements. fiber type B. Circles, OTDR measurements of fiber elongation under longitudinal strain; line, linear least-squares fit to strain measurements.

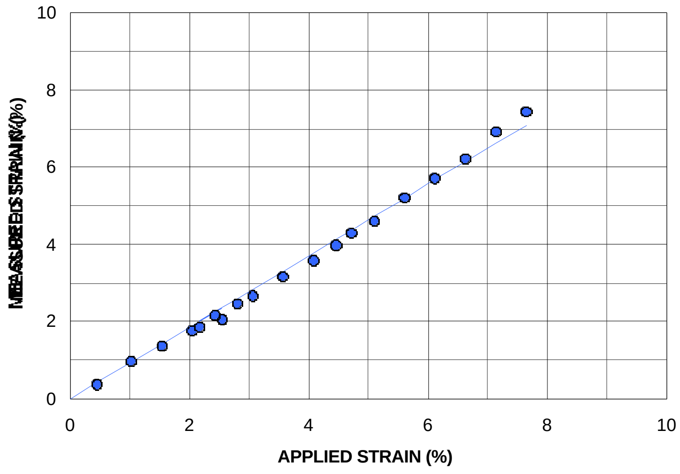

Figure 9.- Typical strain response of polymeric optical fiber type C. Circles, OTDR measurements of fiber elongation under longitudinal strain; line, linear least-squares fit to strain measurements.