A Fiber Bragg Grating Measurement System for Monitoring Optical Fiber Strain

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Abstract

A practical method has been developed for deploying an optical fiber containing a strain sensor into fiber and cable processing equipment while simultaneously monitoring the strain sensor. The sensing system employs the use of fiber Bragg gratings and is able to produce an accurate history of dynamic stresses in the optical fiber during processing, cabling, and installation events. The sensing system acquires an optical spectrum with an equivalent stress range of 0.74 GPa and a resolution of 3 MPa at a rate of 7.2 kHz.

Keywords

Fiber, Processing, Cabling, Bragg Grating, Reliability

1. Introduction

The field reliability of cabled optical fiber is determined by the fatigue behavior of the glass fiber, the strength distribution, the in-service stress, and all the process and installation stress events leading up to in-service life. Most lifetime predictions are based on knowledge of proof test stresses and in-service stresses only. Dynamic processing stresses experienced during events like coloring, buffering, ribboning, stranding, jacketing, and installation need to be incorporated as well. However, these processing stresses are often difficult or impossible to quantify by direct means. For example, unloading from the proof test stress is critical to the lifetime of the fiber, but there are no direct means for measuring it. The proof test stress itself is usually measured indirectly using a gauged pulley. Fiber stresses during cabling should be incorporated into reliability models, but direct fiber stress measurements are nearly impossible. Installation stresses can be measured, but only the average stress over meters of fiber. Localized and dynamic fiber stresses during installation are unknown.

The purpose of this paper is to introduce a method for direct measurement of dynamic stresses in optical fiber during processing, deployment, and in-service lifetime. This method employs the well known strain dependence of fiber Bragg gratings.[1] Fiber Bragg gratings have been used to measure static loads in ribbon cables[2,3] and connectors[4]. The novelty of the method presented in this study lies in the simplicity and speed in which the strain of the grating is captured and the ability to actively monitor fiber strain while it's being deployed into processing equipment. Previous studies were able to monitor fiber strain in only stationary fiber.

2. Fiber Stress Measurement System

2.1 Fiber Bragg Grating

Fiber Bragg Grating (FBG) sensors offer significant advantages over more traditional strain sensors such as electromagnetic noise immunity, high sensitivity, compactness, and simplicity of fabrication. Of greater importance for optical fiber is that the sensor can be embedded directly into the material subjected to stress. The FBG is a wavelength selective device created by forming a grating that modulates the index of refraction of an optical fiber. The grating period and the effective index of refraction determine the center wavelength (Bragg wavelength) of the reflected optical spectrum [5, 6]. The gratings used in this study were approximately 1 cm in length.

The shift of Bragg wavelength varies linearly with strain and temperature. The relationship between longitudinal stress and Bragg wavelength at a constant temperature is given by Equation 1 [7].

$$\frac{\Delta\lambda_{bragg}}{\lambda_{bragg}} = \varepsilon_{zz}\left(1-\left(\frac{{n_{eff}}^2}{2}\right)\left(\rho_{12}-\nu\left(\rho_{11}+\rho_{12}\right)\right)\right) \quad (1)$$

ρ_{11} and ρ_{12} are the strain optic coefficient and ν is poison's coefficient. ε_{zz} is the longitudinal strain.

Assuming silica behaves in a linear elastic fashion one obtains the following dependence of center wavelength on stress;[η]

$$\frac{\Delta\lambda_{bragg}}{\lambda_{bragg}} = \left(1-\left(\frac{{n_{eff}}^2}{2}\right)\left(\rho_{12}-\nu\left(\rho_{11}+\rho_{12}\right)\right)\right) * \frac{\sigma_{zz}}{E} \quad (2)$$

E (73 GPa) is the Young's modulus of silica.

It is not possible to separate the effect of the temperature from the effect of the strain with only one grating. To prevent temperature from confounding the strain measurement, one can adjust the reflected optical spectrum using the results of a sister grating, which experiences just the temperature event. Of course, the

[η] Typical fiber process strain levels are less than or equal to 1%; and therefore, the non-linear portion of the stress – strain curve for silica can be ignored.

other option is to control the temperature during the measurement event. This is what was done for this study.

2.2 Measurement System Overview

The measurement system is based on a FBG sensor and a grating spectrometer to measure the optical spectrum. When a fiber experiences stress, the characteristics of the reflected optical spectrum generated by the fiber Bragg grating changes.[1] Figure 1 shows the three major stress phenomena which affect the reflected optical spectrum of a FBG. All three can be observed by a grating spectrometer: Center wavelength, Bandwidth, and Spectrum splitting.

Transverse loading of the FBG causes birefringence and the reflected spectrum is split into two peaks. Two spectral peaks are generated within the Bragg grating because the effective index of refraction for light polarized in the direction of loading is higher than the effective index of refraction for light polarized orthogonal to the transverse loading direction. Complex loading such as bending, torsion, and the onset of transverse stresses may increase the bandwidth of the reflected spectrum.

Figure 2 shows the schematic of the measurement system used in this study. An Amplified Spontaneous Emission (ASE) light source which is broad band, is used to interrogate the FBG as it traverses through a process or handing event that subjects the fiber to tensile stress. The ASE is coupled into the sensing fiber by a fiber optic coupler. A portion of the ASE spectrum is reflected by the grating and coupled into the grating spectrometer by the fiber coupler. The reflected light spectra are then incident on the grating within the spectrometer, which spatially disperses the spectra onto a linear array camera. The linear camera converts the spatially dispersed spectrum into light intensity as a function of wavelength.

A spectrum with a wavelength range of 13 nm and resolution of 0.05 nm is acquired at a rate of 7.2 kHz. This allows for the monitoring of the reflected spectrum as the Bragg grating travels through the stress event. A computer is used to analyze the resulting data and convert it to the stress/time history experienced by the fiber. Critical to this measurement system is the ability to deliver fiber into the process equipment while simultaneously monitoring the grating within the fiber. This will be discussed more in the experiment section.

2.3 Sensor Calibration

For the tensile calibration of the Bragg sensor, a comparison between the center wavelength shift of the FBG and the measured stress obtained from a strain gauge load cell was performed. The results of this comparison are shown in Figure 3.

3. Experiments

3.1 Tensile Testing

A simple tensile test was performed as an initial test of this measurement system. The fiber was attached to a universal-testing machine[γ] using the usual dual capstan method and loaded in tension to approximately 0.5 GPa. The resulting change in center wavelength of the grating is shown in Figure 4 to closely match the results of the strain gauge load cell. As expected variations in load with time are easily observed.

3.2 Fiber Processing Simulation

To simulate typical fiber process events, a laboratory apparatus consisting of two belted capstans and a weighted pulley was used. A schematic of this test apparatus is shown in Figure 5. The first capstan pays in the fiber from a payout reel. As the fiber enters the first capstan, it is subjected to near zero tensile load. When the fiber is pulled through the capstan, the fiber is loaded in tension by the weighted pulley and loaded transversely by the pressure from the belt. The tension in the fiber is maintained from the exit of the first capstan, around the pulley to the exit of the second capstan. This fiber processing simulation has the common components (capstan, pulleys, belts and adjustable tension) of a typical fiber manufacturing process; and therefore, the Bragg sensor should experience stress events similar to actual stress events in typical fiber and cabling manufacturing processes.

3.3 Fiber Payout Method

The Bragg grating sensor is spliced into a length of single-mode fiber such that there is 250 m of fiber on either end of the grating. This fiber is then wound onto a payout reel constructed of aluminum. The payout reel has the same dimensions as a typical plastic shipping reel. A fiber pigtail is spliced onto one end of the fiber and is connected to the laser via a fiber optic coupler. Critical to this measurement technique is the ability to deliver fiber into process equipment while maintaining access to a stationary end of the fiber. The reel is placed on its side such that the flanges are oriented in a horizontal fashion as illustrated in Figure 5. The other end of the fiber is threaded through the fiber processing apparatus. When the fiber pays into the fiber processing apparatus it simply winds off the stationary aluminum reel imparting twist into the fiber at a rate of approximately 2 twists per meter. The induced torsional stress is small, less than 28 MPa (4 kpsi).

Once the fiber passes through the fiber handling apparatus it is wound onto a conventional fiber reel. Data collection is initiated just before the grating enters the fiber handling apparatus. Note that the fiber handling apparatus must be stopped before the pigtail portion of the grating fiber is reached. The grating and associated fiber can be reused.

3.4 Experiment Plan for Processing Simulations

Three processing experiments were conducted to examine the ability of the measurement system to capture stress events experienced by the fiber. Two processing parameters were varied, processing speed and the dead weight load as shown in Table 1.

[γ] Instron Corp., Canton, MA.

Table 1. Simulated fiber processing events.

	Speed	Load
Test 1	1 m/s	1.083 kg
Test 2	1 m/s	1.389 kg
Test 3	2.5 m/s	1.389 kg

The processing speeds used in this study simulate those used in the cabling of fiber, but are below speeds typically used in coloring and proof testing. The dead weight loads in Table 1 will impart stresses in excess of most fiber processing events and approach those used in proof testing. Note that the configuration of the fiber, θ, through the pulleys and capstan remained constant.

4. Results and Discussion

Figure 6 shows the stress profile resulting from Test 1. The measurement system was able to capture the gross stress events as well as small variations in stress as the fiber traveled through the process simulation. Initially the stress is low as payoff from the stationary reel is under minimal stress (time segment AB). At roughly point B, the grating experiences what appears to be slight compression just as it enters the first capstan (segment BC). As the grating travels through the capstan (segment CD), it rapidly experiences tension. In approximately 30 milliseconds, a fiber travel distance of 3 cm, the stress rises from near zero to 0.5 GPa as the grating enters the high stress region of the test. After it leaves the first capstan, the stress is essentially constant with rapid oscillations on the order of 7% of the mean tensile load (segment DF). The relatively stable stress event (point E) corresponds with travel over the weighted pulley. As the grating enters the second capstan, the process of fiber stress relief begins. The unloading stress profile for segment FG is symmetric to the loading segment BC. When the grating exits the second capstan the stress in the grating is rapidly unloaded. The unloading rate from the second capstan is approximately 15 GPa/s.

These results are particularly interesting from a fiber reliability point of view. The stress event in Test 1 is similar to the proof testing or coloring of fiber. Proof testing is a critical step in the process history of optical fiber in that it is responsible for establishing the minimum strength of the fiber. Reliability engineers have attempted to incorporate the main stress events of proof stress, loading, and unloading into their models. The unloading event receives particular attention in that it is the last opportunity for a flaw near the proof stress to grow subcritically. With this measurement method it is possible to obtain a direct measure of the actual unloading event. Furthermore, it is possible to quantify the variability in the proof test stress. This could lead to increased accuracy in lifetime predictions and provide valuable input into the design of fiber processing equipment.

Figure 7 shows the results from Test 2 where the load was increased by 300 grams. The stress profile was similar to that in Test 1 with the exception that the stress increased to 0.6 GPa.

Figure 8 shows the results from Test 3 where the speed was increased to 2.5 m/s. The duration of the stress event is reduced by 2.5 times as one would expect; however, the high frequency oscillations have been reduced. Note that the small oscillations in stress after fiber unloading are dampened by the take-up reel at a time near 1500 ms.

The data from Tests 2 and 3 illustrates the necessity for direct information on applied stresses when changing processing speeds. In Test 3 the variability in applied stress decreased as the speed was increased, but the opposite could have easily been true if increased speed introduced vibration into the apparatus.

The application of this dynamic stress measurement technique extends beyond fiber processing. The measurement system demonstrated in this study holds promise for measuring dynamic stresses in fiber during cabling, cable installation, severe weather or other events that produce significant cable strain. Of particular importance is the deployment of cabled fiber in under-sea applications where the consequences of fiber failure are severe.

5. Conclusions

Engineers are constantly redesigning fiber manufacturing and cabling technologies. In doing so they must have accurate knowledge of fiber strain in order to stay within established guidelines. A fiber optic sensing system has been developed that can be deployed in a manufacturing or field environment to measure dynamic stress in optical fiber during processing and deployment events. It uses the well known strain dependence of fiber Bragg gratings and provides a means for high speed data acquisition and real time monitoring as the sensor passes through processing equipment.

Fiber stress histories were obtained on several simulated fiber-processing events. Tensile stresses from loading and unloading, weighted pulleys, and winding were obtained and analyzed.

The data from this strain measurement scheme can be input into existing mechanical reliability models that incorporate multiple stress-time histories. In this way one can accurately evaluate the consequences of design and process changes on long-term reliability of optical fiber in cable. Furthermore, this measurement scheme can be used to monitor long-term stresses in cabled fiber after deployment. Reliability models can be updated with changes in deployed stress states.

6. Acknowledgments

Special thanks to Don Clark, Denise VanZile, and Holly Strzepek, for their assistance in conducting the experiments.

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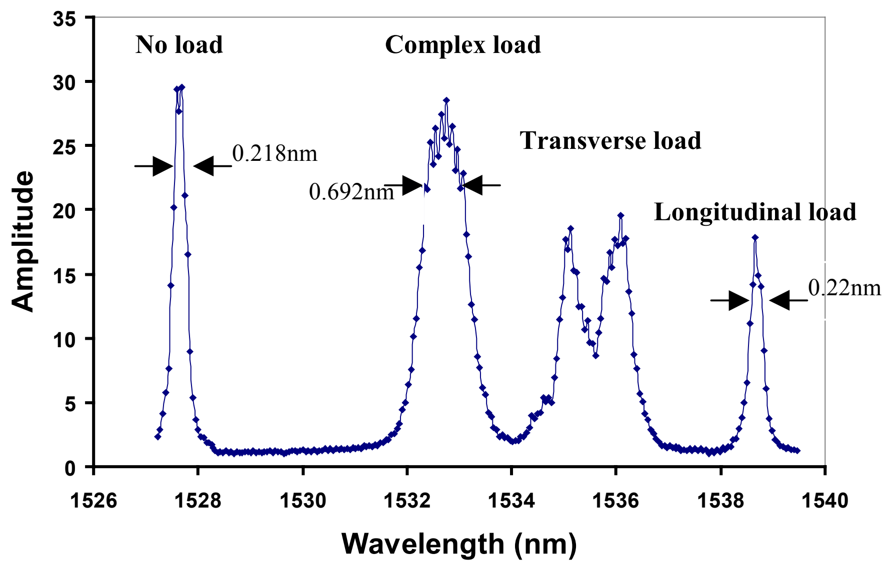

Figure 1. The reflected optical spectrum from a Bragg grating is modified according to the type of loading on the fiber. The phenomena generally monitored are the following: Center wavelength shift, peak bandwidth, spectral splitting.

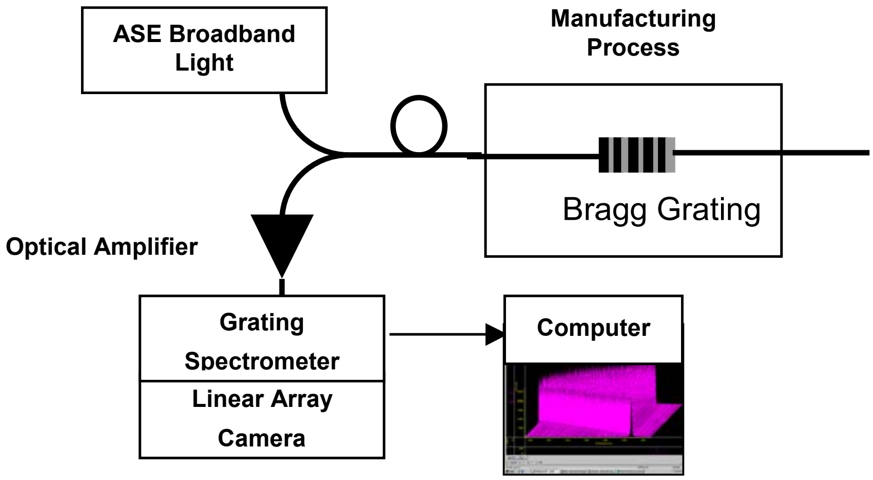

Figure 2. Schematic showing the fiber stress measurement system which is based on dynamically monitoring the return optical spectrum from a fiber Bragg grating.

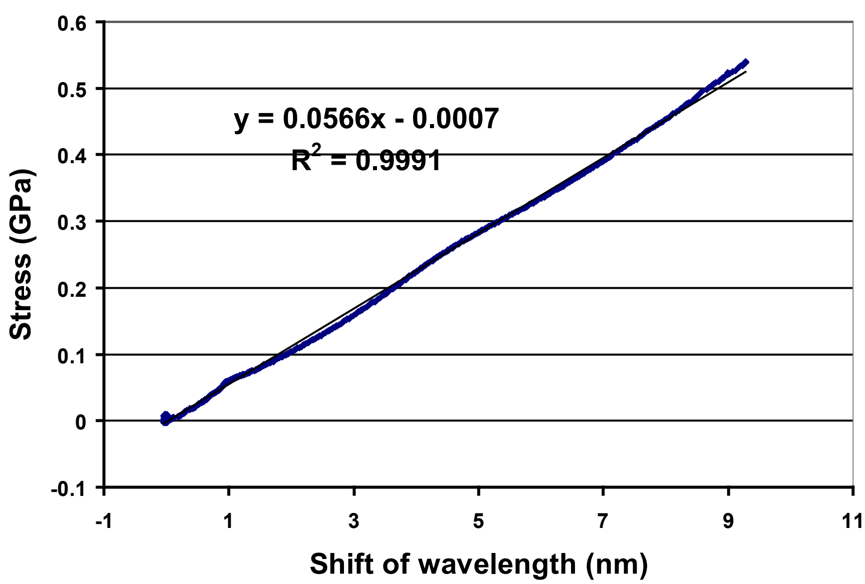

Figure 3. Calibration curve relating center wavelength shift to fiber stress.

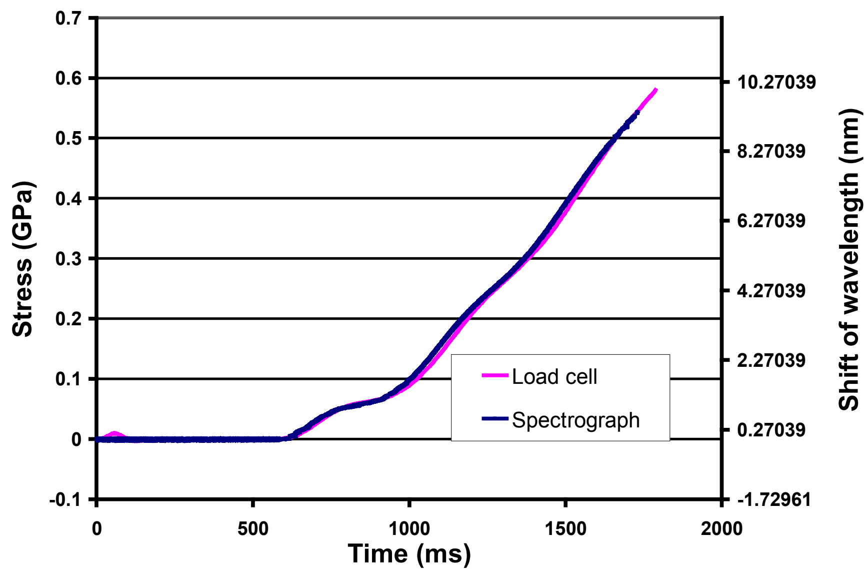

Figure 4. The output from a fiber Bragg grating and load cell obtained by tensile loading the fiber grating in a universal- testing machine.

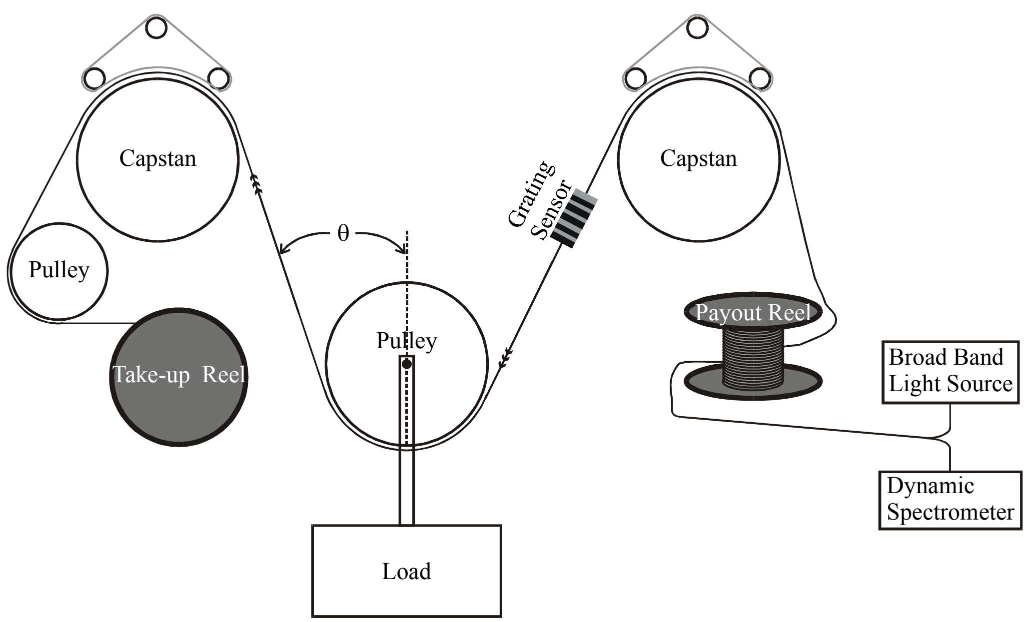

Figure 5. Schematic showing the components of the fiber processing simulator.

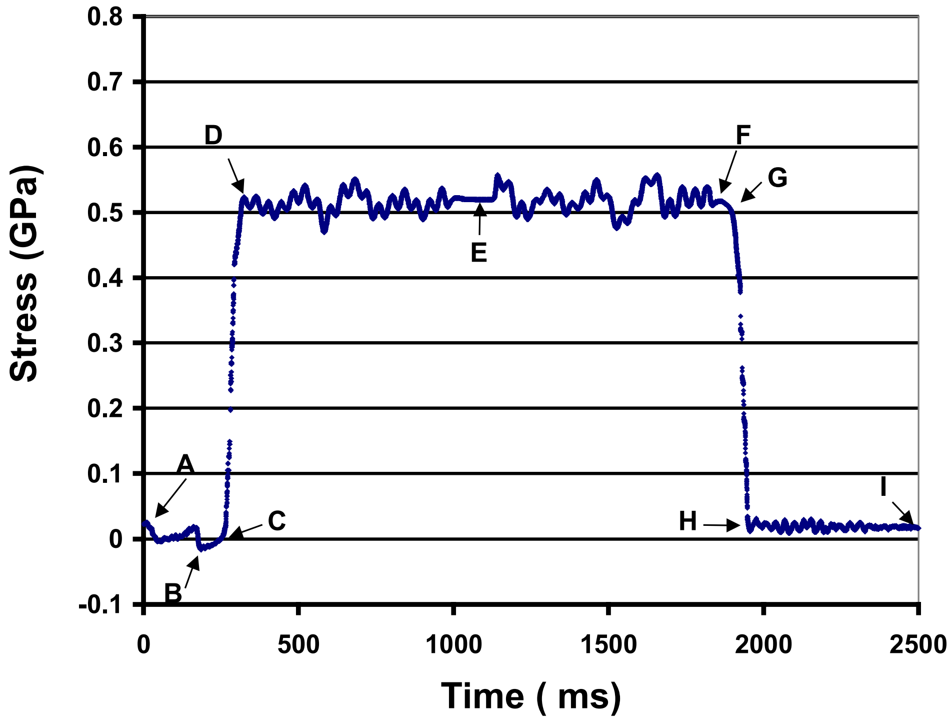

Figure 6. Results from in-process monitoring of the fiber processing simulator under the conditions of Test 1: fiber speed 1 m/s and weight = 1.083 Kg. The labeled points identify specific locations of the Bragg Grating within the fiber processing simulator.

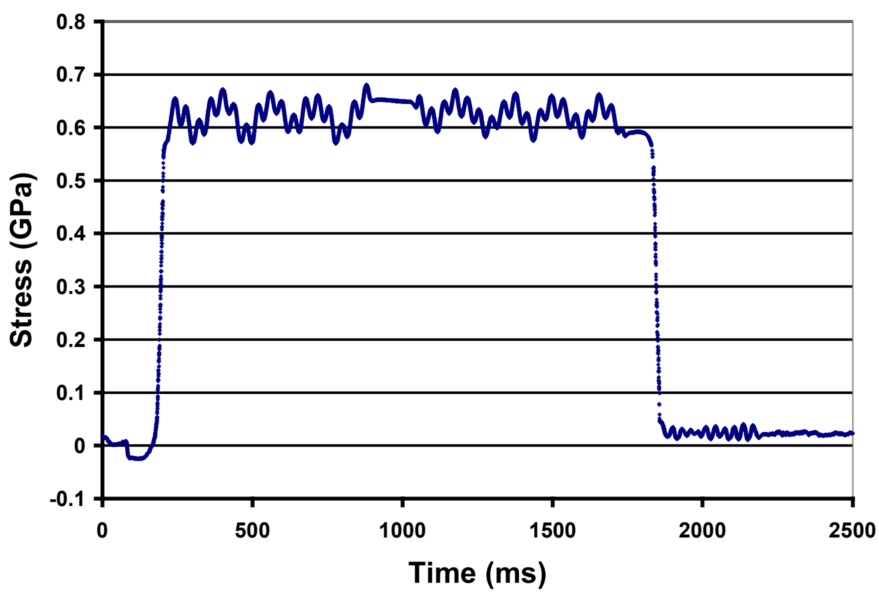

Figure 7. Graph showing the results from in process monitoring of the fiber processing simulator under the conditions of Test 2: fiber speed = 1 m/s and weight = 1.389 Kg.

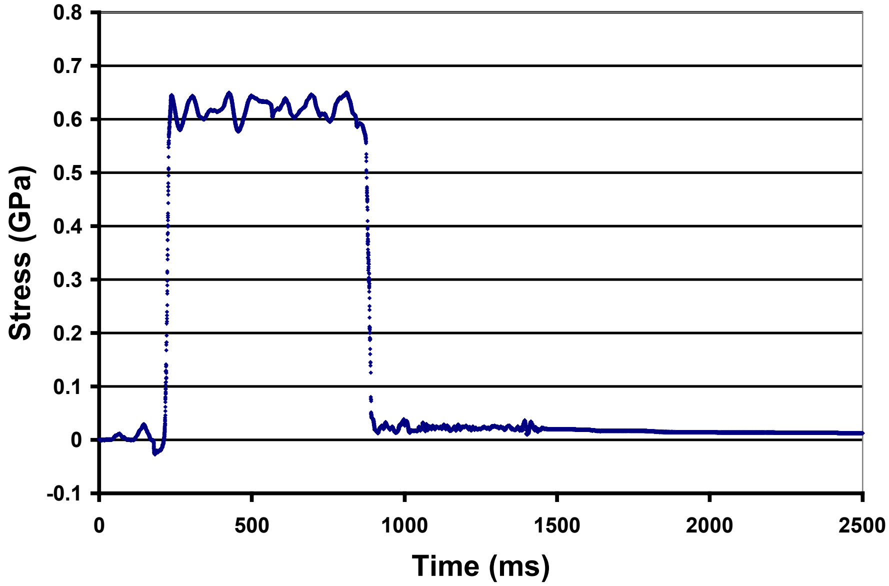

Figure 8. Graph showing the results from in process monitoring of the fiber processing simulator under the conditions of Test 3: fiber speed = 2.5 m/s, weight = 1.389 Kg.

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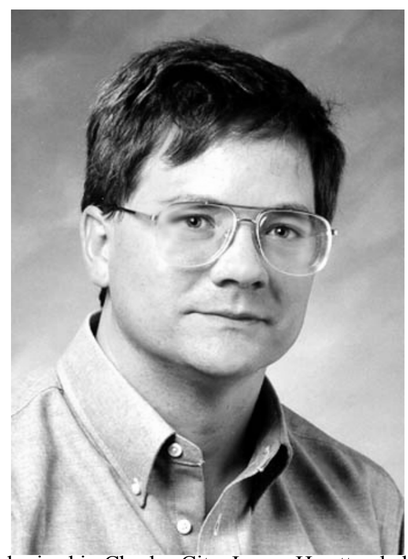

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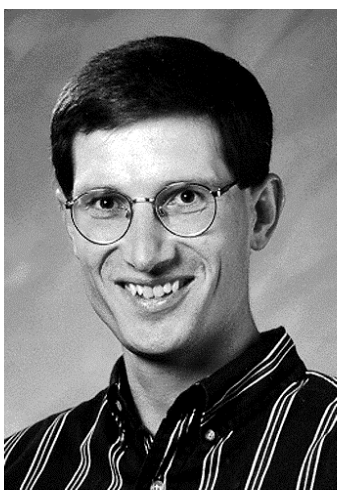

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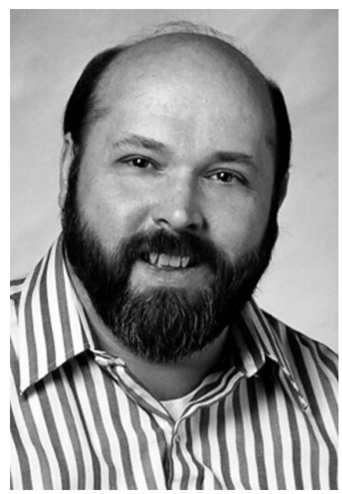

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