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ON FABRICATION AND MECHANICAL PERFORMANCE OF SMART COMPOSITES INCORPORATING FIBER OPTIC SENSORS

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SUMMARY: Fiber optic strain sensors are successfully embedded in glass and carbon fiber reinforced polymer (GFRP and CFRP) tendons during pultrusion. The specific application is the use of the smart composite reinforcements for strain monitoring in innovative bridges and structures. A comprehensive reliability study of the pultruded tendons with the embedded sensors was performed encompassing mechanical tests under ordinary laboratory conditions as well as under conditions of low and high temperature extremes. In these tests, the strain output from the embedded sensors was compared to that from surface-affixed extensometers. There was an excellent degree of conformance between the two strain-monitoring devices. The assessment of the fiber optic sensors further entailed the examination of their fatigue and short-term creep behaviour. For these tests as well, there was a good agreement between the strain readings from the embedded sensors and the extensometers. Finally, to simulate conditions encountered in concrete structures, the long-term performance of the smart composites in alkaline environments, with the simultaneous application of tensile loads, was examined. The results were very encouraging: The embedded fiber optic sensors were not affected by the harsh environment and continued to perform satisfactorily.

KEYWORDS: CFRP/GFRP Smart Tendons, Pultrusion, Fiber Optic Sensors, Reliability Study, Fatigue Behaviour, Creep Behaviour, Alkaline environments.

INTRODUCTION

Fiber optic sensing techniques are currently being investigated for strain monitoring in critical structures in civil and marine engineering, including for example bridges and hydroelectric dams. Resistance to EMI losses, inherent corrosion resistance, minimal need for cabling, a very small size which implies little or no disturbance to the substance being monitored, and the ability to make absolute strain measurements are among the properties that make fiber optic sensors more attractive than traditional strain gages. Two popular types of fiber optic sensors that are currently being used are the Fabry-Perot and Bragg Grating sensors.

Fiber optic sensors have been used to monitor the state of structures made up of many different materials including steel, aluminum, concrete and composites. The sensors can be surface mounted on a structure or test sample in much the same manner as traditional foil gages. A suitable adhesive is used to bond the sensor to the substrate. The characteristics of the adhesive are very important because an effective strain transfer from the substrate to the sensor must to be achieved.

A new field of research has emerged in recent years which involves the production of smart composite materials in which the fiber-optic sensing element and accompanying lead are embedded inside the composite material during fabrication. The embedded sensor is thus well protected from harsh external environments as well as from rough handling during the construction phases of large projects. It has been shown that very effective strain-transfer characteristics from the host composite material to the sensing element are achievable by using embedded fiber optic sensors. For example, Kalamkarov et al. [1-3] have shown that strain readings from fiber-optic sensors embedded in GFRP and CFRP smart tendons closely match corresponding readings from externally mounted devices such as extensometers, under both static and dynamic loading conditions. The smart composites used for these experiments were manufactured by the process of pultrusion.

Despite the fact that pultrusion is one of the fastest and most cost-effective composites manufacturing processes, well suited to produce prestressing tendons and reinforcing bars, it has received relatively little attention in the area of smart composites, and there are currently only a few publications on this subject (Friebele et al.) [4], (Kalamkarov et al.) [1-3,5,6]. Perhaps, this can be partly attributed to the fact that pultrusion is quite complex in detail as a consequence of the many mechanical, chemical and physical factors that are simultaneously involved in the process. However, the incorporation of fiber optic sensors within the process of pultrusion during the manufacture of smart composites, can provide valuable insight as to many of the underlying processes that occur prior, during, and after the consolidation of the product (Kalamkarov et al.) [6].

While fiber optic sensors and smart composite materials have shown promise in replacing or strategically complimenting traditional materials and strain gages, there is not a great deal of data available that reflect upon their long-term behaviour, which, as expected is significantly affected by the surrounding environment. For civil and marine applications, the composite materials and associated fiber optic sensors will encounter, in addition to mechanical stress, external conditions of high and low temperature, humidity and chemical ion exposure. Since typical applications have expected life spans of over 50 years, investigators must rely on accelerated tests to examine the effect of such factors. Erdogan et al. [7] reported that the decay of reflectivity in an optical fiber is fairly small at temperatures up to 300^{o}C and that losses are negligible over a life-span of 50 years if the temperature during that period never exceeds 80^{o}C. Habel et al. [8] investigated the effect of highly alkaline solutions (typical in concrete) on optical fibers and their coatings. It was discovered that neither acrylate nor polyimide coatings can sustain environments with pH values of 11-14. Hence, optical fibers with these types of coatings were not considered suitable for direct contact with concrete. However, if embedded in a protective composite material, these sensors could be incorporated in composite structures to monitor the health of these structures.

A comprehensive reliability analysis of the embedded fiber optic sensors, however, should not be limited to the study of their performance in reactive solutions or under conditions of temperature extremes. Equally important is the fatigue behaviour of the fiber optic sensors. In particular, it will be of interest to determine if the sensors still perform adequately after enduring a large number of stress cycles, and if they retain their accuracy and repeatability. As well, it is known that creep deformations may cause unacceptable dimensional changes or distortion and ultimately final failure. Both composites and more traditional materials such as steel can exhibit creep behaviour, although it is more often related to elevated service temperatures. Appropriately, another objective of the current research is to investigate the creep characteristics of the composite tendons with the embedded fiber optic sensors and assess their suitability for monitoring in long-term service conditions.

In summary, the present research involves a study of the performance of embedded fiber optic sensors under conditions of static and dynamic loading in variable temperature environments. Also, the fatigue and creep behaviour of the smart pultruded tendons will be assessed. The fiber optic sensors that are embedded in CFRP and GFRP pultruded rods are of the Fabry-Perot and the Bragg Grating type.

FIBRE OPTIC SENSORS

In this study, the first fiber optic sensors that were embedded during the pultrusion of fiber reinforced rods were of the Fabry-Perot type. These sensors and the demodulating equipment are currently off the shelf items. The Fabry-Perot sensor has been developed to use a broadband light source as opposed to laser light. It is highly sensitive and can make precise, linear, and absolute measurements. Two multimode fibers are inserted and fused into a larger glass capillary tube with an overall diameter of 200-250 microns. The ends of the fibers, which are inserted into the capillary, are polished and contain a semi-reflective coating. The distance between the fused locations defines the gauge length of the sensor. The sensor is designed such that a predefined air gap exists between the two polished optical fiber ends within the capillary tube. Hence, some of the light introduced to the sensor reflects from the end of the lead-in fiber, while some travels through the air gap and reflects from the second polished fiber end. In the reflective mode of operation, both reflections are transmitted back through the lead-in fiber to a detector. As external forces are applied to the sensor, the length of the air gap changes and hence, so does the phase difference between the two reflections. Several demodulation techniques are available to evaluate this phase difference and relate it to strain. Belleville and Duplain [9] describe one such device, which uses a Fizeau interferometer to aid in the measurement of the Fabry Perot cavity length, in more detail.

The other type of fiber optic sensor used in the present study was of the Bragg Grating type. Bragg Grating sensors are based on creating a pattern of refractive index differentials directly onto the material of the fiber core. This may be achieved by directing two laser beams operating in the ultraviolet, into the fiber from the side. An interference pattern results with alternating bright and dark fringes. At the zones of constructive interference, permanent optical damage is induced at sites occupied by germanium atoms as a result of the intensity of the ultraviolet light. This changes the refractive index of the glass material and creates a periodic pattern in the fiber, which resembles a diffraction grating. Fibre gratings selectively reflect certain wavelengths and transmit others. Which wavelengths are transmitted and which ones are reflected depend on both the refractive index of the core material as well as the spacing of the pattern. Changes in temperature or pressure will change the refractive index of the core material and hence cause a change in the wavelengths of peak reflection (or transmission). The presence of mechanical strain along the length of the Fibre will have a similar effect since it will change the grating spacing. Measurements of these wavelength shifts provide the basis of operation of Bragg Grating sensors.

MATERIALS AND EQUIPMENT

Central to the current study was the fabrication of carbon and glass FRP tendons using pultrusion. 9.5 mm-diameter rod stock was produced using a customized pultrusion machine (Kalamkarov et al.) [1-3,5,6]. The reinforcing fibers (E-glass or carbon rovings) were pulled from a creel system into a shaping die. The die is equipped with three temperature zones, each with its own PID temperature controller. Prior to entering the die, the fibers are wet out in a dip-type wet bath and then distributed evenly over the rod’s cross section by a series of specially machined high-density polyethylene cards. One roving traveled a straight path through the cards to the center of the rod. This center roving was used to carry the optical fiber in experiments where a fiber optic sensor was required to be embedded in the composite rod. The pulling force was maintained by a set of counter rotating wheels, which provided consistent pulling speeds.

The fiber glass rovings used are continuous E-glass filaments formed into a single end reinforcement, free from catenary and treated with 0.45 nominal wt.% sizing which is a silane based and compatible with most resin systems. The carbon rovings used had a standard epoxy-based sizing. The rods were produced using a urethane modified bisphenol-A based vinyl-ester resin system known for its good mechanical properties and excellent processability. Two types of organic peroxide catalysts were used to cure the resin, di-peroxydicarbonate and tert-butyl peroxybenzoate. Adequate release from the die was achieved by using an internal lubricant. The 9.5-mm diameter carbon rods were pulled with 22 ends of rovings giving a volume fraction of 62.5%, while their glass counterparts were pultruded with 26 ends giving a volume fraction of 64%. Finally, die temperatures of 120°C, 150°C, and 120°C at the three zones, as well as a pulling speed of around 25 cm per minute were found to produce good quality FRP rods.

EXPERIMENTAL AND DISCUSSION

As a first attempt at embedding a sensor in a pultruded rod, an unmodified Fabry-Perot fiber optic sensor was added to the fiber feed side of the pultrusion process. The forward end of the sensor lead was bonded to one of the carbon fiber rovings and fed into the die. From the location at which it was bonded, the sensor had to pass through two of the fiber feed cards before entering the die (Kalamkarov et al.) [6]. After the sensor had passed through the die and had been embedded in the composite rod, the pultrusion process was stopped to enable trimming away of several carbon fiber rovings in order to pass the pigtail and connector through the die.

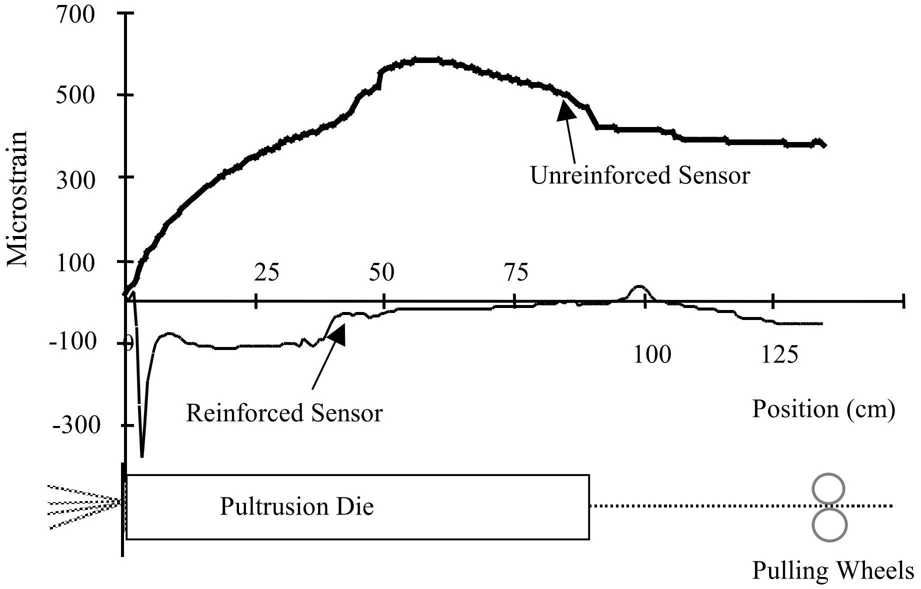


Fig. 1 Comparison of outputs from reinforced and unreinforced Fabry-Perot sensors during pultrusion

The result of this first trial was a length of carbon fiber rod with an embedded Fabry-Perot sensor. However, when the sensor was tested using the fiber readout unit, it was found to have failed. Several other experiments were conducted in an attempt to embed Fabry-Perot sensors in carbon and glass FRP rods during pultrusion. It was observed that the vast majority of these sensors failed shortly after the consolidated rods had exited the die. These post-fabrication failures were attributed to the radial shrinkage of the composite tendon as it cooled down from the die temperature to room temperature. The shrinkage in turn exerted an external pressure on the sensing element, causing it to collapse. To overcome this problem, a novel method was developed to pre-reinforce the sensors prior to pultrusion (Kalamkarov et al.) [6]. These pre-reinforced sensors were pultruded in the same way as their unreinforced counterparts and they did survive the process and were still operational after the end of the experiment. Fig. 1 shows the strain output from the pre-reinforced sensor together with the output of the unreinforced sensor. Subsequently, all Fabry-Perot sensors were pre-reinforced and this ensured their successful pultrusion in both carbon and glass FRP tendons.

Microstrain

Unlike Fabry-Perot sensors, Bragg Grating sensors showed enhanced survivability during pultrusion and it was not deemed necessary to pre-reinforce them. Fig. 2 shows the strain plots obtained from dry and normal pultrusion runs superimposed. A dry pultrusion run involves passing of a sensor and the composite fiber rovings through the heated die but with the rovings not soaked in resin. Useful information about pultrusion can be extracted from such plots. The difference between the two curves in Fig. 2 is due to the curing of the resin. For example, the peak strain during normal pultrusion is much higher than during dry pultrusion. This is likely to have been caused by an increased thermal expansion of the sensor due to the exothermic reaction accompanying pultrusion and by the expansion of the surrounding resin due to the increased temperature. Also to be noted is the fact that, as the product exits the die, the difference between the two curves represents the process-induced strains.

To assess and characterize the overall behaviour of the embedded fiber optic sensors, mechanical testing of the pultruded tendons was carried out in ordinary laboratory conditions by applying various proof loads to the tendons while continuously monitoring strain via the embedded optical sensors and a standard extensometer clipped to the pultruded rod. The smart FRP tendons were subjected to two basic waveforms in order to evaluate their performance. The first waveform was a trapezoidal waveform whereby the load was ramped from a low value (typically 100 N) to a peak value of about 3000 to about 11000 N, at a slow rate of 90 N/sec. The load was held at this level for 20 seconds and then ramped back down to the initial value at the same rate. The second waveform to which the smart tendons were subjected was a sinusoidal one. The frequency was one cycle per minute (0.0167 Hz), and a typical range through which the load was cycled was from 400 to 5000N.

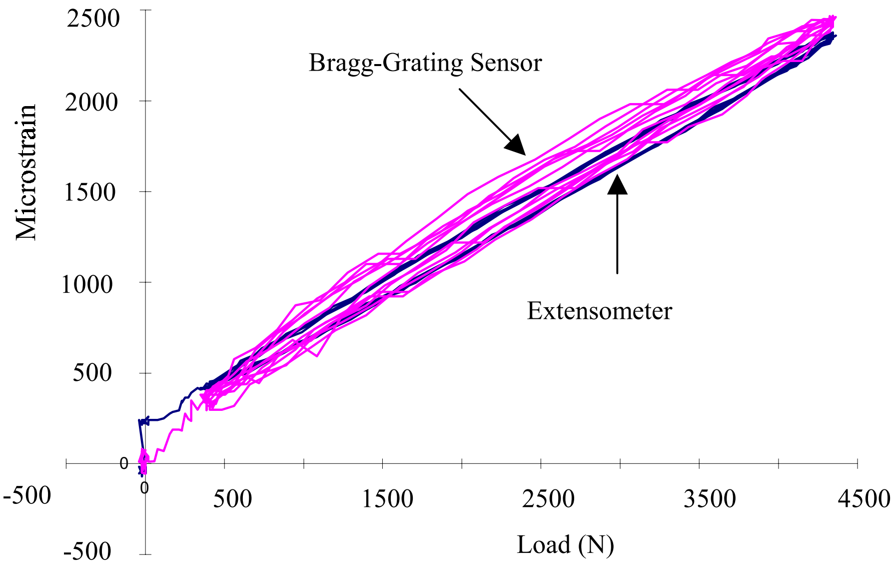


Fig. 3 Strain from extensometer and embedded Bragg-Grating sensor in a glass tendon subjected to a sinusoidal waveform (peak load of 4500 N) at room temperature

Fig. 3 shows the results from a sinusoidal test performed on a GFRP tendon with an embedded Bragg Grating sensor. The data are plotted as microstrain vs. load for a number of applied load cycles. It is evident that there is a high degree of conformance between the strain readings from the two devices over the entire load range. As well, both the sensor and the extensometer show a good degree of repeatability as the load is cycled.

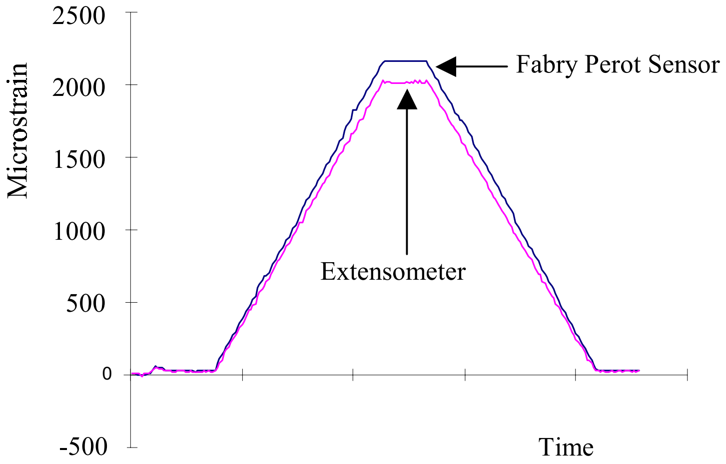


Fig. 4 Strain vs. time plot from extensometer and Fabry-Perot sensor in glass tendon subjected to trapezoidal loading (7000 N)

Many more tests (trapezoidal and sinusoidal) were performed on both GFRP and CFRP tendons with embedded Bragg Grating sensors (Kalamkarov et al.) [3]. The results indicate that the strain output from the sensors was accurate and consistent and agreed well with that from the extensometers.

Fig. 4 shows the results from a trapezoidal test performed on a GFRP tendon this time with an embedded Fabry-Perot sensor. The microstrain vs. time plot shows that there is a good agreement between the sensor and the extensometer. At the peak loads the discrepancy is less than 8% which is quite reasonable given the resolution of the extensometer and the Fabry-Perot sensor. The same conclusions can be reached from the other experiments performed on GFRP and CFRP tendons with embedded Fabry-Perot sensors (Kalamkarov et al.) [3]

One of the primary objectives of the present research was the study of the behaviour of the fiber-optic sensors when the tendons in which they are embedded are exposed to both low and high temperature extremes. The experiments entailed subjecting the GFRP and CFRP tendons to sinusoidal and trapezoidal waveforms of about 12 kN magnitude inside a temperature chamber. The temperature in the chamber was varied from –40°C to +60°C in increments of 20°C. Fig. 5 shows a microstrain vs. time graph for a GFRP tendon with an embedded Fabry-Perot sensor at 60°C. The sensor strain output is compared to that from an extensometer. At the beginning of the test, prior to the application of any load (other than a very small preload), the Fabry-Perot strain reading was about 210 microstrain. This is a purely thermal strain caused by the expansion of the glass tendon. This thermal strain was factored out of both the sensor and the extensometer strain readings by calibrating (nulling) the two strain-monitoring devices after the temperature in the chamber had reached steady state and just before any load application. Thus, the strain outputs in Fig. 5 pertain to purely mechanical strain. As the figure indicates there is a remarkable agreement between the two strain-monitoring devices over the entire load range. Many more temperature tests were performed on both GFRP and CFRP tendons, and they all indicated that the sensor readings conformed very well to the corresponding extensometer readings and theoretical results (Kalamkarov et al.) [1]. Thus, ambient temperatures falling within the range of -40 to +60°C do not affect the performance of the embedded Fabry-Perot sensors.

As mentioned earlier, another major objective of the research was to study the fatigue behaviour of the fiber optic sensors, by examining the performance of the smart FRP reinforcements under conditions of cycling loading. To this end, glass and carbon FRP tendons with embedded Fabry-Perot and Bragg Grating sensors were subjected to a sinusoidal load waveform of 1 Hz frequency and ranging in magnitude from 6.5 kN to 11 kN (a stress ratio of 0.6). Testing was carried out for a duration of 140,000 to 350,000 cycles. The strain values from the embedded sensors were compared to those from externally mounted extensometers. Fig. 6 shows the results for such a fatigue test performed on a carbon FRP rod with an embedded Bragg Grating sensor. It is seen that the sensor is unaffected by the fatigue load and its strain output is repeatable and accurate even after 350,000 cycles. Similar tests were performed on other CFRP and GFRP tendons with embedded Fabry-Perot and Bragg Grating sensors (Kalamkarov et al.) [2]. The tests indicated that the performance of the fiber optic sensors is not degraded after many thousands of cycles of applied tensile loading.

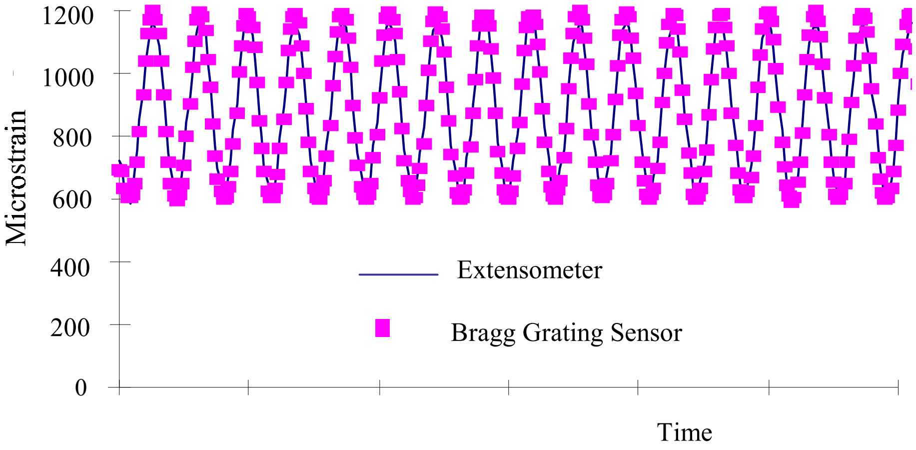


Fig. 6 Strain from extensometer and Bragg Grating sensor embedded in a carbon FRP tendon subjected to tension-tension fatigue for 350,000 cycles.

In addition to fatigue, another objective of the research is to characterize the long- and short-term creep behaviour of the embedded fiber optic sensors and examine their suitability for monitoring long-term service conditions. The goal is to investigate the interaction of the composite host material and the embedded sensor under conditions of sustained load levels and to assess the composite tendons themselves.

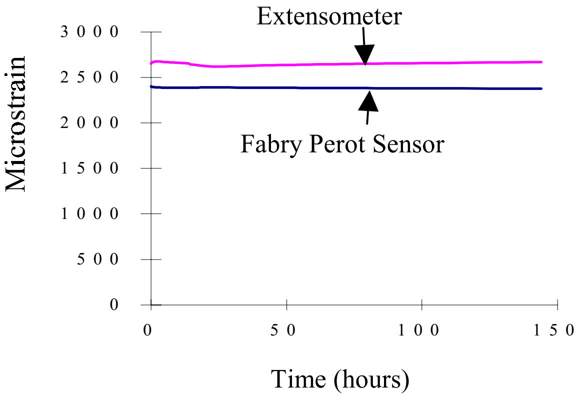
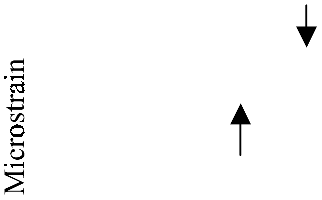


Fig. 7 Glass FRP tendon at 9 kN for 140 h.

Both carbon and glass FRP tendons were chosen for short-term creep testing. Both tendons contained an embedded Fabry-Perot sensor. The applied load was 9 kN (for a period of 140 hours) for the case of the glass tendon, and 13.5 kN (for a period of 350 hours) for the case of the carbon tendon. From Fig. 7 it can be seen that the output from the Fabry-Perot sensor is practically uniform over the entire duration of the test. Similar results pertain to the carbon tendon (Kalamkarov et al.) [2]. It may therefore be concluded that Fabry-Perot sensors do not exhibit a short-term creep behaviour at the given experimental conditions.



Longer term testing was subsequently performed with the object of gaining more detailed insight into the behaviour of the tendons and the sensors. This long-term testing was conducted in a caustic environment that may simulate conditions encountered in concrete structures wherein the composite rods may be used as prestressing tendons. Both glass and carbon FRP tendons with embedded Fabry Perot sensors were chosen for this testing. The tendons were located inside an environmental chamber through which an alkaline solution was circulated by a pump. The solution (pH. of 12.8) was composed of 0.32 mol/L KOH, 0.17 mol/L NaOH and 0.07 mol/L $Ca(OH)_2$. The tendons were also subjected to a constant load of about 11 kN. Testing was carried out for a period of 2.5 months. Fig. 8 shows a comparison of the strain outputs from the sensor embedded in the carbon tendon and an externally bonded foil gage. It can be seen that there is a good agreement between the optical sensors and the gage. More important however, is the fact that the combination of the highly alkaline solution and sustained load has no effect on the behaviour of embedded sensors for the duration of the tests. The same results pertain to the Fabry-Perot sensor embedded in the glass tendon (Kalamkarov et al.) [2].

CONCLUSION

This study has demonstrated the pultrusion process can be used to successfully integrate Bragg Grating and Fabry-Perot fiber optic sensors into the composite reinforcements. It was shown that it was necessary to pre-reinforce Fabry-Perot sensors prior to pultrusion. Bragg Grating sensors show a greater survivability in the pultrusion process and do not need to be pre-reinforced.

Mechanical testing was carried out in order to assess the overall behaviour of the smart FRP tendons and compare the performance of the embedded sensors to that of traditional strain monitoring devices such as extensometers. Glass and carbon FRP tendons with embedded Fabry-Perot or Bragg Grating sensors were subjected to trapezoidal and sinusoidal load inputs. Testing was carried out at room temperature as well as in low and high temperature environments (-40°C to +60°C). In all cases there was a very good agreement between the embedded sensor and the extensometer.

Fatigue testing of the smart FRP tendons entailed subjecting them to 140,000-350,000 cycles of load varying in magnitude from 6.5 kN to 11 kN. The output from the embedded Fabry-Perot and Bragg Grating sensors showed an excellent conformance with that from the extensometer. Thus, many cycles of applied load had no effect on the performance of the sensors.

Subsequent tests indicated that Fabry-Perot sensors embedded in composite materials did not exhibit long-term creep behavior even if the composites were loaded in an alkaline environment. Short-term creep tests performed under ordinary laboratory conditions had previously shown the same results. Thus, smart composite materials with embedded fiber optic sensors have potential for significant benefit in the long-term monitoring of strain levels in field applications.

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