Comparison of recoated fiber Bragg grating sensors under tension on a steel coupon

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ABSTRACT: One of the key elements in a structural health monitoring system is the sensing element and data acquisition system. One type of fiber optic sensor used to measure strain is the fiber Bragg grating (FBG). As part of the fabrication process, fibre Bragg gratings are recoated after the grating has been written to maintain the strength and flexibility of the fibre by protecting the exposed glass from damage. Acrylate and polyimide are two types of recoat material typically used on fibre Bragg grating sensors. Previous work has suggested that acrylate and polyimide coatings are comparable except in the transmission of strain. Acrylate recoated fibres are thought to perform well under short periods and at low temperatures and low strains. However, polyimide coated fibres perform well under higher strains and temperatures. This work is a controlled comparison of polyimide and acrylate recoated fibres for Bragg grating strain sensors. The comparison was carried out using a tension test coupon with recoated FBG and electrical strain gauges bonded to its surface. During the tension test, the load was applied in 40 $\mu\varepsilon$ steps until the strain readings reached approximately 200 $\mu\varepsilon$. The load was then incrementally decreased back to zero. At each step, the load was held for approximately 1.5 minutes. In this study, FBG sensors from two manufacturers were compared.The error between the first manufacturer's sensor readings and the strain gauges was well within ±5 $\mu\varepsilon$. On the other hand, the second manufacturer's sensors did not perform as well. These readings were substantially lower than the corresponding electrical strain gauges readings and varied from 7% to 13% below expected strain readings. This study demonstrates that bonded FBG sensors can reliably measure strain, but not all manufacturers are producing recoated FBG sensors to the standard required for strain sensing in civil structures.

1 INTRODUCTION

One of the key elements in a structural health monitoring system is the sensing element and data acquisition system. In the past few years, there has been a significant focus of research on fiber optic sensors. One type of optical sensor used to measure strain is the fiber Bragg grating. A fiber Bragg grating is comprised of periodic changes in the refractive index of the core located in a section of single mode fiber (Hill et al. 1978). This modulation creates a sort of filter which causes all wavelengths except one to be transmitted through the grating as shown in Figure 1. The reflected wavelength is called the Bragg wavelength, λ_B, and is defined by the equation

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

where n_{eff} is the effective refractive index in the core and Λ is the spatial period of the refractive index modulation.

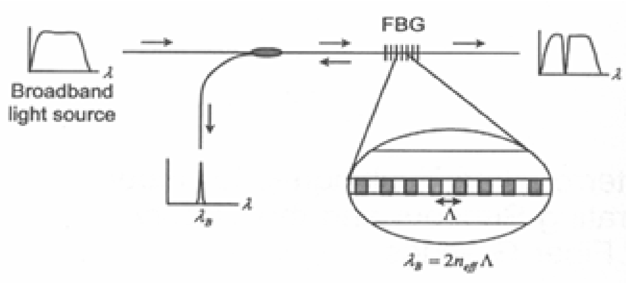

Figure 1. Operating principle of the fiber Bragg grating sensor (Yu & Yu 2002)

The grating length is typically 1 to 2 cm and the bandwidth of the reflected signal, which is dependent on the grating length, is typically ~0.05 to 0.3 nm (Yu & Yu 2002).

Bragg gratings can be fabricated using different methods. A typical method involves placing a mask pattern over the optical fiber and shining UV light through it to change the refractive index of the core. However, before the grating is written into the core of the fibre, the outer fibre coatings must be stripped away, either mechanically or chemically. Fibre Bragg gratings are then recoated after the grating has been written to maintain the strength and flexibility of the fibre by protecting the exposed glass from damage (Tarpey et al. 2002). Acrylate and polyimide are two types of recoat material typically used on fibre Bragg grating sensors. Their characteristics are found in Table 1 (Inaudi et al. 1996):

Table 1. Main characteristics of different fibre coatings.

Property	*Acrylate microcoating*	*Polyimide microcoating*
Stripping	mechanical or chemical	chemical
Transmission of strain across coating	good for short times, low tensions and T<35ºC	excellent
Mechanical protection	very poor	very poor
Chemical protection	moderate	moderate
Thermal expansion coefficient	very low 0.5×10^{-6}	very low 0.5×10^{-6}
Cost	low	high

According to table 1, the characteristics of the acrylate and polyimide coatings are comparable except in the transmission of strain. Acrylate recoated fibres perform well under short periods and at low temperatures and low strains without any noticeable creep. On the other hand, polyimide coated fibres perform well under any condition. Therefore, researchers have recommended the use of polyimide coated fibres for Bragg grating sensors (Inaudi et al. 1996). In this work, we compare the performance of bonded FBG strain sensors using acrylate and polyimide recoating.

This study involves the design and construction of a steel tension test specimen. The purpose of the steel coupon is to provide a constant strain environment during the test. After the coupon is fabricated, fibre Bragg sensors coated with either acrylate or polyimide are bonded to the coupon. In addition, electrical strain gauges and strain gauge rosettes are installed on the coupon to provide a comparison in the readings. Finally, tension tests are conducted on the steel specimen to monitor the performance of the fibre Bragg sensors.

This study will examine the performance of fibre Bragg grating sensors coated with different materials. The results of this study will provide the information necessary in determining if the type of recoat material affects transmission of strain from a specimen to the sensor.

2 EXPERIMENTAL PROGRAM

2.1 *Design of the Steel Tension Test Specimen*

The steel test coupon was designed according to the ASTM A30-97a standard (ASTM International 2000). The dimensions were chosen such that three fibre optic sensors and a strain gauge can be aligned with each other on each side of the coupon. This will help ensure that all sensors experience the same strain during the tension test. The thickness of the coupon was 12.7 mm (½”) and the width of the grip section was 50.8 mm (2”). At the reduced section, the width was 38.1 mm (1 ½”) and the gauge length was 203.2 mm (8”) (Figure 2).

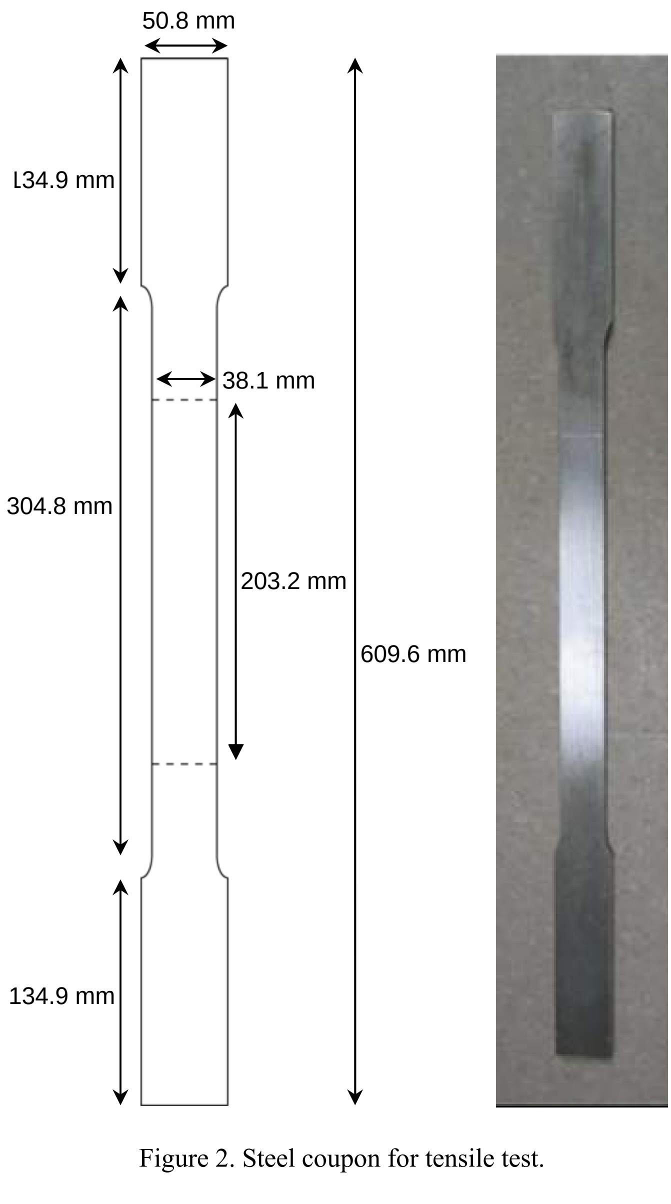

Figure 2. Steel coupon for tensile test.

2.2 *Instrumentation*

A total of 11 sensors were bonded to the steel coupon. Each side of the steel coupon consisted of three types of fibre Bragg grating sensors, an electrical strain gauge and a strain gauge rosette (Figure 3). The purpose of the electrical strain gauges was to provide a comparison in strain readings for the fibre optic sensors. The rosette consisted of three strain gauges aligned at 0º, 45º, and 90º. The readings from the rosettes will help ensure there is no rotation in the steel coupon during the tests. A weldable strain gauge was also attached on one side of the steel coupon.

The fibre Bragg grating sensors were obtained from two manufacturers. In this paper, the manufacturers will be referred to as Supplier 1 and Supplier 2. Sensors with acrylate and polyimide recoating were obtained from Supplier 1. The sensors from Supplier 2 were recoated with acrylate. The FBG sensors were bonded to the coupon using the M-Bond AE-10 epoxy which is produced by Intertechnology Micro-Measurements Division. A 4:1 ratio of resin and curing agent was used to create the epoxy.

The electrical strain gauges (model No. CEA-06-250UW-350) were also manufactured by the Intertechnology Micro-Measurements Division. They had a resistance of 350.0 ± 0.3% Ω and a gauge factor of 2.095 ± 0.5%. The epoxy used was also M-Bond AE-10 to ensure that the electrical strain gauges were bonded identically to the coupon as the FBG sensors.

The weldable strain gauge (model No. CEA-06-W250A-120) was manufactured by the Intertechnology Micro-Measurements Division. It had a resistance of 120.0 ± 0.4% Ω and a gauge factor of 2.060 ± 0.5%. The strain gauge was spot welded to the coupon using a Vishay Measurements Group Portable Strain Gauge Welding/Soldering Unit (model No. 700).

The strain gauge rosettes (model No. N31-FA-10-120-11) were manufactured by Showa Measuring Instruments Co., Ltd. They had a resistance of 119.8 ± 0.3% Ω and a gauge factor of 2.11 ± 1.0%. The epoxy used was M-Bond 200 which is produced by Intertechnology Micro-Measurements Division.

The locations of the sensors are shown in Figures 3 and 4. The fibre optic sensors and electrical strain gauges were arranged such that both sides of the coupon were mirror images of each other. Therefore, the electrical strain gauge on side B would be directly behind the electrical strain gauge on side A and so forth.

After the sensors were bonded to the coupon, several coatings were layered on the sensors to protect them from damage. These coatings included nitrile rubber coating, Teflon tape, butyl rubber sealant and aluminum foil.

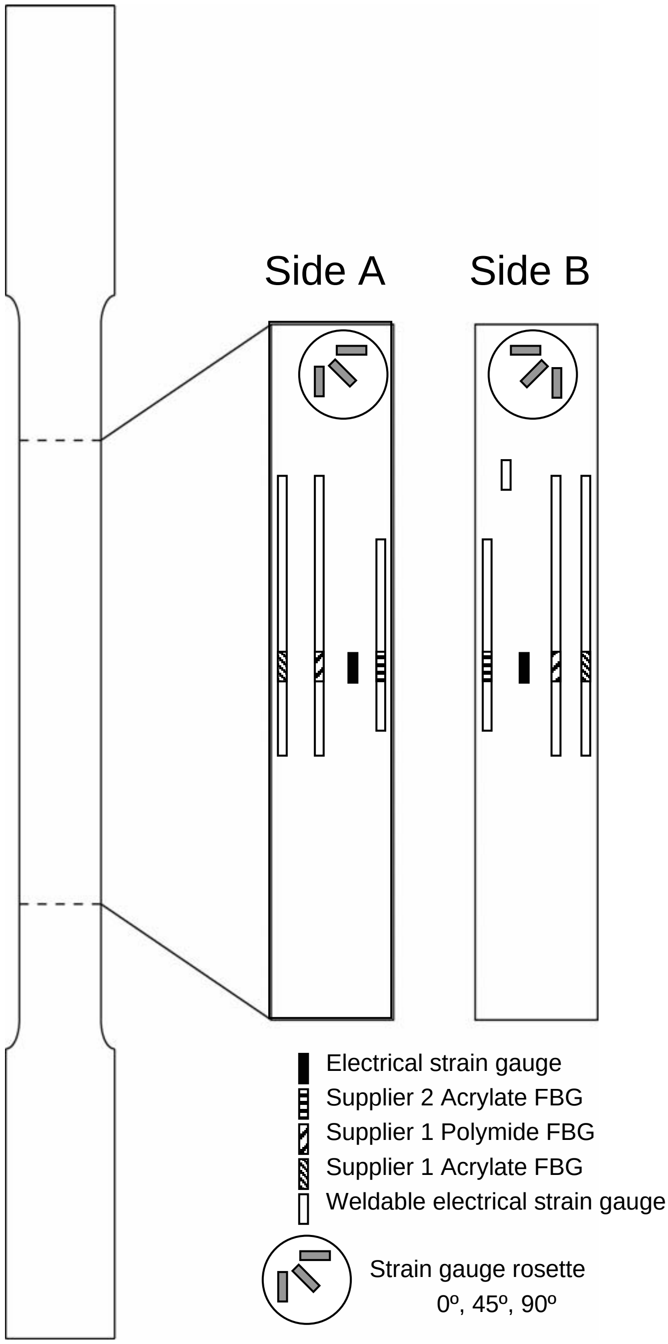

Figure 3. Sensor configuration on steel tension coupon.

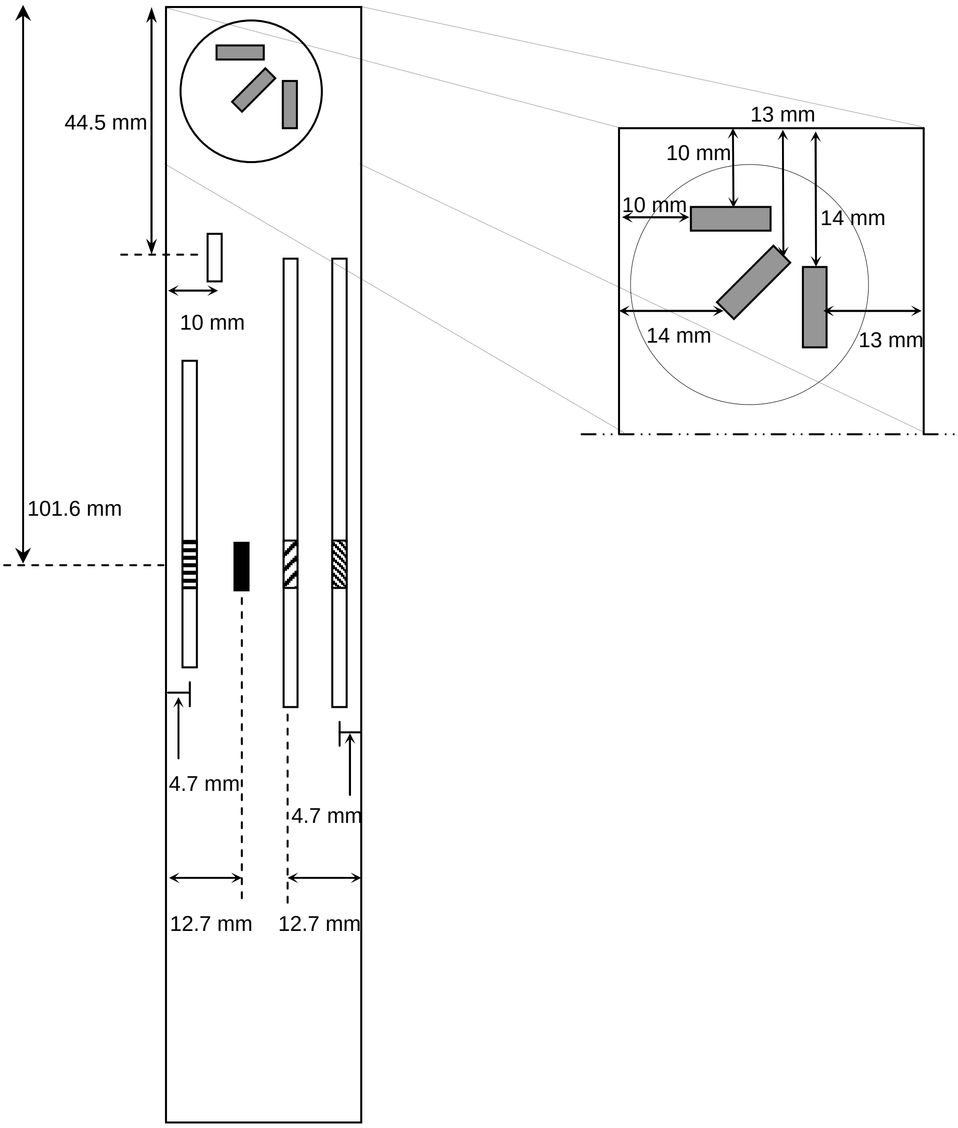

Figure 4. Location of sensors on side B of tension coupon.

2.3 *Tension Test of Steel Specimen*

The coupon was placed into a 1000 kN Mechanical Testing and Simulation (MTS) machine and secured with grips (Figure 5). The strain gauges were connected to a National Instruments data acquisition system. The fibre optic sensors were connected to the SHM Systems 5100A FBG readout unit (Figure 6). This unit requires each FBG to have a corresponding ID tag which stores information such as centre wavelength and gauge factor. The ID tags for the fibre Bragg sensors were programmed with the information in Table 2.

Table 2. Properties of fibre Bragg grating sensors.

Channel #	*Manufacturer*	*Sensor Name*	*Recoat Material*	*Wavelength (nm)*	*Gauge Factor*	*Coupon Side*
1	Supplier 2	S2 ACR A	Acrylate	1539.000	0.75	A
2	Supplier 1	S1 POLY A	Polyimide	1539.400	0.75	A
3	Supplier 1	S1 ACR A	Acrylate	1539.700	0.75	A
4	Supplier 2	S2 ACR B	Acrylate	1539.030	0.75	B
5	Supplier 1	S1 POLY B	Polyimide	1539.300	0.75	B
6	Supplier 1	S1 ACR B	Acrylate	1539.300	0.75	B

In total, three tension tests were conducted on the steel coupon. Each tension test involved increasing the load to obtain 40 $\mu\varepsilon$ increments. The load was increased until the electrical strain gauge on side A (SG A) reached 40 $\mu\varepsilon$. This occurred approximately at 4 kN. After holding the load at this level for a period of time, the load was then increased until SG A reached 80 $\mu\varepsilon$. The load was then held again for a small amount of time. This process continued until the strain reached 200 $\mu\varepsilon$ where the load was approximately 20 kN. The load was then incrementally decreased back to zero. At each increment, the load was held for approximately 1.5 minutes.

Figure 5. Experimental test setup with coupon in MTS machine.

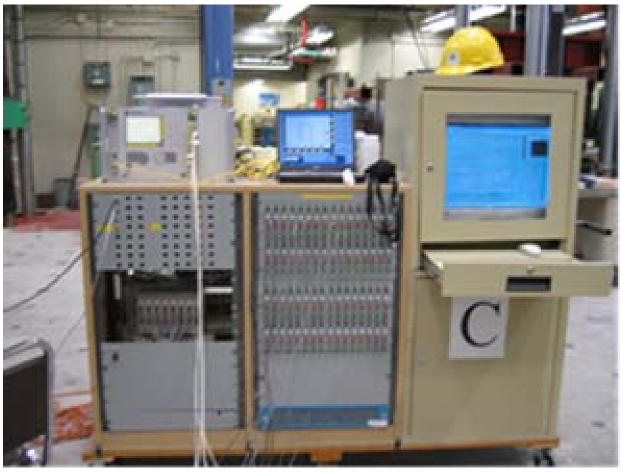

Figure 6. Electrical and optical sensor data acquisition systems.

3 ANALYSIS OF DATA AND DISCUSSION

The fiber Bragg grating sensor is used for structural health monitoring because it responds to strain through a wavelength shift. This feature is advantageous because it does not depend on the amplitude of the signal and as a result, is less susceptible to sensor failure due to signal loss or degradation. When the sensor is bonded on or embedded in a material, the reflected wavelength will change when the grating undergoes thermal or mechanical strain. This is a result of a change in period of the grating. The wavelength shift $\Delta\lambda_B$ is defined by

$$\Delta\lambda_B = \lambda_B\,(\varepsilon(1-\rho_e) + \beta\Delta T) \quad (2)$$

where λ_B is the initial peak wavelength, ε is the strain induced, ρ_e is the effective strain optic coefficient, β is the apparent thermal strain and ΔT is the temperature change. The strain optic coefficient is a constant that relates the change in the index of refraction to strain. It is given by

$$\rho_e = n^2/2*[p_{12} - v(p_{11} + p_{12})] \quad (3)$$

where p_{11} and p_{12} are components of the strain-optic tensor, n is the refractive index and v is Poisson's ratio. For a silica fiber, the typical values for these parameters are $p_{11} = 0.113$, $p_{12} = 0.252$, $v = 0.16$, and $n = 1.444$ (Moses 1971, Duan et al. 2001). This will give a strain optic coefficient of 0.2017. Therefore, assuming $\Delta T \approx 0$ and using Equations (2) and (3), a 1 $\mu\varepsilon$ strain will cause a 1.22 pm wavelength shift at a Bragg wavelength of 1550 nm. The previous Equation (2) can also be written as, assuming $\Delta T \approx 0$,

$$\Delta\lambda_B = \lambda_B\,\varepsilon GF \quad (4)$$

where GF is the gauge factor. The gauge factor is a value which expresses a sensor's sensitivity to strain. The gauge factor typically varies from 0.75 to 0.8 and depends on the manufacturer and type of fibre used.

The results from all three tests were very similar. Therefore, the following graph will only show the results from the second test. In this graph, the signals from the fibre optic sensors and two electrical strain gauges are shown (Figure 7). The purpose of the strain gauge rosettes was to ensure that there was no rotation on the coupon during the test and therefore, its signals are not required for comparisons with the fibre optic sensors. In Figure 7, there is approximately a 35 $\mu\varepsilon$ difference between the lowest and highest readings at maximum load.

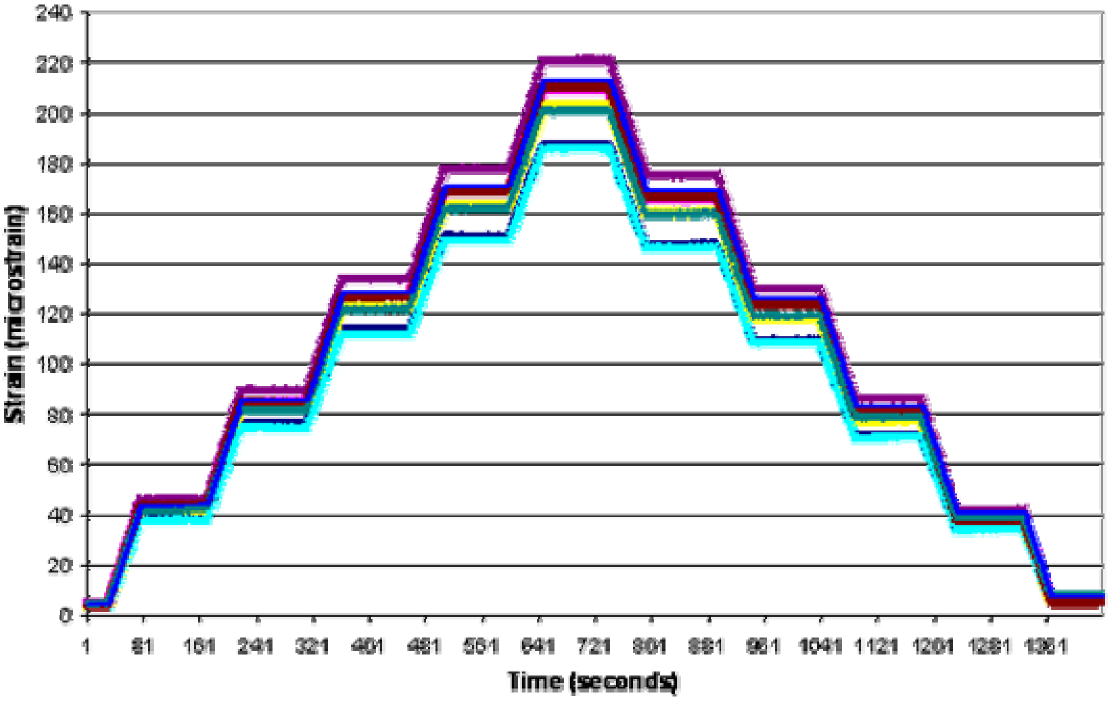

Figure 7. Signals from fibre optic sensors and strain gauges.

In the results, the electrical strain gauge on side B (SG B) returned strain values slightly higher than SG A. Therefore, there may have been some slight bending in the coupon during the test. Therefore, the fibre optic sensors on side A will have experienced strains equivalent to SG A and the sensors on side B will have experienced strains equivalent to SG B.

The signals from the Supplier 2 acrylate sensors both returned lower strain readings than the electrical strain gauges. At the maximum load, there was approximately a 14 με (7%) difference between the strain gauge and FBG on side A and there was a 26 με (13%) difference between the strain gauge and FBG on side B.

The signals from the Supplier 1 acrylate sensors returned readings close to the electrical strain gauges. At maximum load, there was a 2 με (1%) difference between the strain gauge and FBG on side A and there was a 3 με (1.5%) difference between the strain gauge and FBG on side B.

The signals from the Supplier 1 polyimide sensors returned strain readings higher than the strain gauges using a GF of 0.75. However, in past research, it was determined that a gauge factor of 0.8 was more appropriate for these FBG sensors (Rivera 2004). Therefore, the gauge factor was changed to 0.8 for the polyimide sensors. In this case, at the maximum load, there was a 5 με (2.5%) difference between the strain gauge and FBG on side A and there was a 6 με (3%) difference between the strain gauge and FBG on side B.

The results from the Supplier 1 sensors were quite favorable as seen in Table 3. It was observed that the optimum gauge factor varies depending on the type of recoat material on the sensor. For acrylate coated sensors, the appropriate gauge factor was approximately 0.75 and for polyimide coated sensors, the appropriate gauge factor is 0.8. Using these gauge factors, the error between the Supplier 1 sensor readings and the strain gauges was well within the accuracy of the SHM Systems 5100A FBG readout unit which was ±5 με. On the other hand, the Supplier 2 sensors did not perform as well as the Supplier 1 sensors. The readings from these sensors were substantially lower than the corresponding strain gauges readings. The strain difference in the readings varied between 7% and 13% and thus, it was impossible to determine an appropriate gauge factor for the sensors. A maximum error of 26 με or 13% was observed.

From the results of the tests, the performance of fibre Bragg grating sensors depends on the manufacturer and the technique by which they were fabricated. The acrylate sensors from Supplier 1 and Supplier 2 performed quite differently from each other although they had the same recoat material. Since this test was performed at room temperature and at low strains, it is difficult to determine which recoat material, if any, performs better in varying temperatures and strains.

Table 3. Strain readings from fibre optic sensors and strain gauges in the second tension test.

Load (kN)	Strain Readings from Sensors (με)							
	S2 Acry A	*S1 Poly A*	*S1 Acry A*	*SG A*	*S2 Acry B*	*S1 Poly B*	*S1 Acry B*	*SG B*
0.0	4.3	4.0	3.8	4.4	3.7	4.5	3.8	4.2
3.8	39.7	41.0	42.3	42.1	38.1	43.2	43.2	43.6
7.9	76.2	79.4	81.8	81.6	74.7	84.1	84.6	85.6
12.0	113.8	119.1	122.4	121.8	111.9	125.5	126.8	128.4
16.1	150.6	157.8	163.1	161.8	148.9	166.7	168.8	170.7
20.1	187.0	196.4	202.7	200.9	185.4	207.3	210.2	212.8
15.8	147.4	155.3	160.3	159.9	146.2	164.4	166.2	168.8
11.6	109.3	115.4	118.4	119.3	108.2	122.1	123.2	126.2
7.4	71.8	75.5	77.6	78.6	70.9	80.7	81.0	83.3
3.3	35.1	36.5	37.5	39.2	34.2	39.0	38.3	40.8
0.0	5.9	5.5	5.2	8.4	5.0	5.9	5.0	7.2

4 CONCLUSION

As structural health monitoring continues to grow as a field of increasing interest for civil engineers, fiber optic sensor technology is thought to be the most promising alternative to conventional sensors. To successfully monitor the condition of a structure, the measurement device must be able to provide reliable and accurate data over long periods of time. The fibre Bragg grating sensor is a one type of optical sensor commonly used to measure strain in civil infrastructure. During the manufacturing process, fibre Bragg gratings are recoated, after the grating has been written, to maintain the strength and flexibility of the fibre by protecting the exposed glass from damage. Acrylate and polyimide are two types of recoat material typically used on fibre Bragg grating sensors.

In this study, tension tests were performed on a steel coupon instrumented with strain gauges and fibre Bragg sensors with different types of recoat material. From the results of the tests, it was observed that the performance of fibre Bragg grating sensors depends on the manufacturer and the technique by which they were fabricated. The acrylate and polyimide sensors from one supplier performed favorably. This study suggests that recoating standards are required for FBG sensors used in civil structural health monitoring.

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