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Fibre optic sensors for high temperatures and fire scenarios

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ABSTRACT: In both industrial applications and fire scenarios, sensing may be required at very high temperatures. Such sensing could be used to monitor and control equipment in industrial situations or to provide an emergency management system in a structural fire. Conventional fibre optic sensors (FOS), however, are limited to relatively low temperatures. Thus, this paper discusses the development of technology for fibre optic sensing at high temperatures.

FOS with a special coating for resisting high temperatures is being employed to measure temperatures and strains on fibre reinforced polymer (FRP) coupons. These sensors are attached to the coupons and tested in a special high temperature material testing facility at Queen's University. This test facility can perform well-controlled tests up to 600°C with a load capacity of 600 kN. The stimulated Brillioun scattering method (SBS) is used to interpret the measurements. Using Optical Frequency Domain Reflectometry (OFDR) on data collected from carbon coated fibres, a relationship between strains and the optical wavelength shifts is discovered. Alongside FOS Particle Image Velocimetry (PIV) method is used to determine the state of strain and deformation in coupons.

To illustrate the potential application in a structure, two full-scale T-beams (4 m span) are constructed with FOS attached to the internal longitudinal reinforcement. These T-beams are strengthened with external FRP, and fire protection for the FRP is provided by sprayed insulation. These beams are then exposed to a standard ASTM fire while under sustained loading.

1 FIRE SAFETY AND SENSING

In 2008, the National Fire Protection Association reported that there were over 500,000 structural fires in the United States causing 2,900 civilian deaths and $12.4 billion in property damage (Karter 2009). In addition to the direct costs of fires, recent collapses such as the World Trade Center disaster and other tall buildings in Madrid and Delft due to fire have emphasized the importance of fire safety.

Although fire safety design of buildings has improved the behaviour of structures in fire, it has not eliminated the hazards of building fires. Current approaches to reducing fire losses employ a more holistic view to fire safety by combining and integrating different technologies. This integration provides early forecasts of the chain of events after the start of a fire. In the forefront of these technologies is sensing. Sensing technology can help emergency responders make critical decisions by detecting fire location and severity, extent of fire spread, and structural integrity.

In addition to fires, structures are prone to other types of damage. Earthquake, fatigue, and vandalism can all cause problems for structures. To detect these types of damage and preserve the health of structures, designers need a range of sensors to predict failure and prevent it from happening. Conventionally used sensors such as smoke detectors, thermocouples, and electrical resistance strain gauges are among these sensors. However having multiple types of sensors in structures is costly and difficult to incorporate. As a result, sensors with the capacity to sense multiple variables simultaneously are gaining popularity. Fibre optic sensors (FOS) are capable of sensing many useful variables such as temperature, strain, displacement, pressure, acceleration, integrity, and cracking extent (Kersey and Dandridge 1990 and Ravet 2009).

2 STIMULATED BRILLOUIN SCATTERING FOR FIBRE OPTIC SENSORS

Stimulated Brillouin scattering (SBS) based sensor systems are distributed sensors that can measure temperature and strain along the entire length of the fibre. Unlike other sensors, the fibre used to transfer the light to the sensing point is also the sensing medium. Thus, continuous temperature and strain distributions can be obtained. SBS is a nonlinear process and the Brillouin frequency shift (BFS) is linearly related to the temperature and strain in the fibre allowing the measurement of strain and temperature simultaneously. Recently, most of the strain sensing using Brillouin scattering has been based on a standard single mode fibre (SMF28) with an acrylate coating, which can only sustain temperatures of 80°C. Obviously, this limitation is insufficient for sensing in fire situations, but sensing fibres with a carbon/polyimide coating have been used to overcome this shortcoming. The temperature limitations are approximately 450°C for this kind of fibre.

Zeng et al. (2002) successfully used SBS based sensors to function as a distributed strain sensor in a reinforced concrete beam with a spatial resolution of 500 mm along a 1650 mm long beam. Additionally, Zou et al. (2004) have reported temperature and strain measurement accuracy of 1.3 ±˚C and15 $\mu\varepsilon$ using SBS based sensors. They reached a spatial resolution of 150 mm.

For the high temperature work presented in this paper, SBS sensing was employed with fibres having a carbon/polyimide coating. For full-scale fire tests of fibre reinforced polymer (FRP) strengthened reinforced concrete T-beams, the fibres were attached to the longitudinal steel to measure strain and temperature. For material tests, the sensing fibres were attached to FRP coupons and tested in a high temperature material testing facility.

3 FRP STRENGTHENING IN FIRE SITUATIONS

FRP materials are increasingly being applied for strengthening or rehabilitating reinforced concrete structures that need to sustain loads higher than originally considered in design, or that have deteriorated from damage such as electrochemical corrosion.

In spite of many advantages of FRPs, such as resistance to corrosion and ease of application; fire resistance remains a significant obstacle to strengthening structural members in buildings and parking garages because of these materials' susceptibility to degradation at elevated temperatures. The weakest link in fire behaviour of the FRP materials is the degradation of the bonding resin (often epoxy resin) when the resin reaches its glass transition temperature.

4 EXPERIMENTAL PRODEDURE

4.1 FRP Specimen Fabrication

The coupons for tension tests were made of unidirectional CFRP plates (Sikadur-S512). The plates were cut in half lengthwise by a wet abrasive diamond blade to reduce the ultimate failure load of the specimen to within the loading capacity of the testing machine. The coupons were 700 mm in length, approximately 25 mm in width ,and 1.2 mm in thickness as shown in

Figure 1. To reduce grip stresses, another layer of CFRP plates was attached to the ends of the coupons as tabs. These 50 mm by 25 mm tabs were attached to the FRP specimen using epoxy adhesive (Sikadur-30). All specimens were cured more than 28 days in room temperature before testing.

4.2 Test Procedures and Instrumentation

To investigate the mechanical behaviour of CFRP material at elevated temperatures, two different types of tests were considered. Four samples were tested under a steady state regime and one sample was tested in a transient regime (Table 1). In the steady state tests, the CFRP samples were heated first and then exposed to tensile forces, while in the transient test, a tensile sustained load was first applied to the sample and later, the temperature was increased until the sample failed. The load was kept constant during the heating period for the transient test.

The mechanical behaviour of the FRP at higher temperatures is dependent on the behaviour of both constituents, i.e. resin and fibre. The mechanical properties of the resin degrade drastically at a temperature known as the glass transition temperature (T_g) which is usually between 50 to 120˚C. Since the FRP may experience significant loss in its mechanical properties near T_g, steady-state tests were conducted at T_g, T_g +20 and T_g -20 °C (Table 1).

Table 1 Specimen information and test regime.

Specimen ID	Test Regime	Temperature (˚C)	Load Level (kN)
1.1	Steady-State	20	
1.2	Steady-State	Resin Tg (110)	
1.3	Steady-State	Resin Tg – 20 (90)	
1.4	Steady-State	Resin Tg + 20 (130)	
2.1	Transient		60 % of ultimate (54.6)

The testing apparatus was an INSTRON universal testing machine (UTM) with a thermal chamber having internal dimensions of 250 mm by 250 mm by 300 mm (height) and a maximum load capacity of 600 kN. Samples were exposed to heating in the middle of the sample; the heated length was approximately 300 mm. The temperature variance in the furnace was less than ±5˚C. The rate of temperature increase was 10˚C/min for all steady-state tests. The same rate was used in the transient tests, but to achieve more stable reading by the FOS, temperature was kept constant for approximately 5 minutes at 100 and 200˚C. Load was applied at a constant rate of 2.5 mm/min in all tests. To prepare more stable reading situations for FOS in steady-state tests, load was kept constant for approximately 5 minutes at some load levels of 20, 40, 60, 70, 75 and 80 kN.[1]

[1] Not all load levels were used for all the tests.

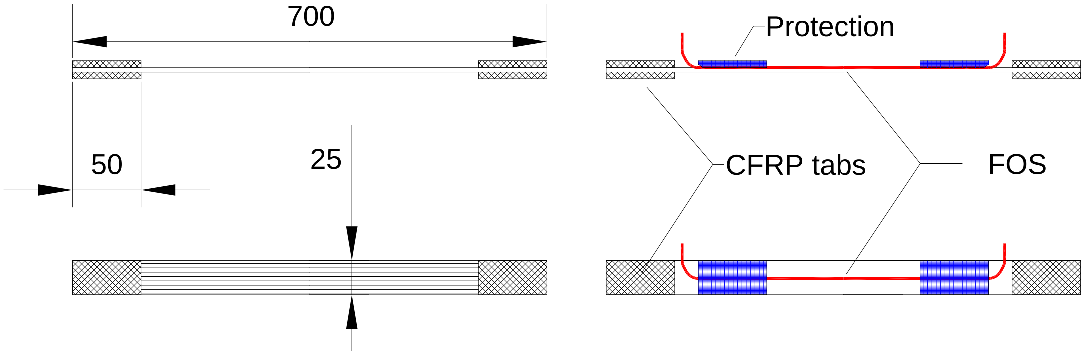

Figure 1: CFRP coupon dimensions and fibre optic sensor locations (all dimensions in mm).

5 INSTRUMENTATION

The important variables were axial deformation and strain, load in the CFRP specimen, and finally temperature of the furnace. Load was captured by the internal load cell of the UTM machine. Temperature was recorded by two type K thermocouples located inside the furnace. The thermocouple readings were in agreement with furnace's target temperature.

The axial strain of FRP samples was measured using particle image velocimetry (PIV) (White et al. 2003). High resolution images were taken during various stages of the test procedure. PIV is capable of tracking the movement of any pixel patches in a sequence of images. This allows for measuring the displacement field in the sample during the test. To measure the axial strain, the displacement of pixel patches similar to those shown in Figure 2 were tracked. The difference in axial displacement of the patches divided by their axial distance gives the strain in that direction. Figure 3 shows a sequence of pictures taken during the transient test. Since the PIV analysis tracks the pixel pattern around a certain point, difficulties arise when the surface texture changes due to thermal effects.

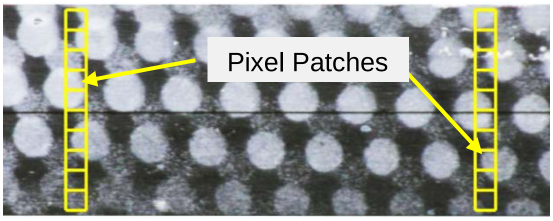

Figure 2 Square pixel patches (yellow squares) on FRP sheet used in PIV analysis.

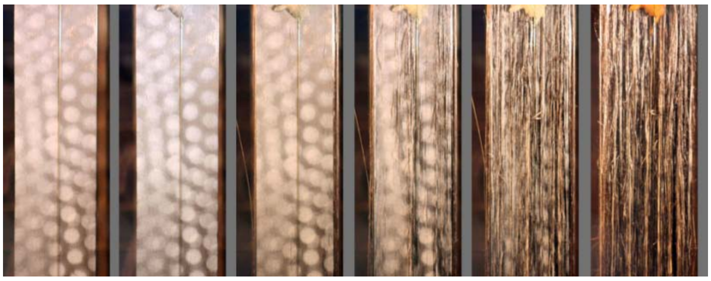

Figure 3 Damage progress during test for specimen 2.1. Temperatures are 28, 77, 183, 200, 210 and 256 ˚C from left to right.

SBS based FOS were installed on the specimen along their longitudinal axis of symmetry as shown in Figure 1. The fibre was attached to the FRP sample at the ends using epoxy glue. The glued parts were kept outside the furnace. To further protect the bond between FOS and the coupon, a protective cover was placed on top of the glued fibre (Figure 4).

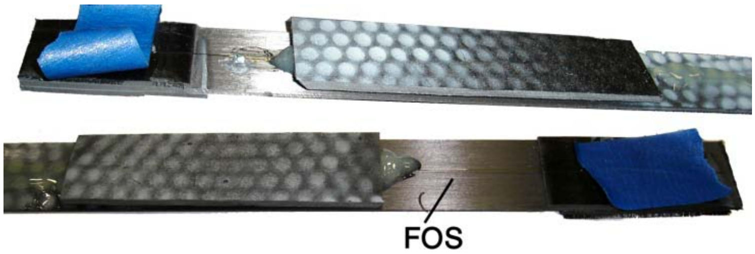

Figure 4 Fibre optic sensor and protective cover installation details.

6 RESULTS

Based on differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) tests on the FRP material, T_g was determined to be 110˚C.

PIV analysis was performed to calculate the strain at several load levels for the test sample 1.1. Knowing the load level and the sample dimensions, these strain values were used to calculate the secant elastic modulus as reported in Table 2.

Table 3 shows the results of the steady-state tests. No significant loss of strength was observed in tests performed at temperatures below T_g. The elastic modulus as reported by the manufacturer is 165 GPa which is in good agreement with the obtained results.

Figure 5 shows a sample coupon before and after a transient test while Figure 6 shows the secant modulus versus temperature during the transient test. The modulus of the material decreases as the temperature rises. The rate of reduction increases dramatically just above the glass transition temperature (110 ˚C).

Table 2 Modulus calculation results for room temperature test at different load levels; strain was calculated using PIV analysis.

Load (kN)	Strain PIV	Stress (MPa)	Secant Modulus (GPa)
40	0.92%	1390	151
60	1.32%	2080	158
80	1.70%	2780	163

Table 3 Steady-state tension test results for FRP at high temperature.

Specimen ID	Temperature (˚C)	Width (mm)	Peak load (kN)	Strength (MPa)	Strength Loss %
1.1	27	24.0	81.6	2830	0.0
1.2	110	24.0	73.1	2540	11.6
1.3	90	24.6	82.1	2780	0.7
1.4	130	23.4	55.3	1970	47.5

Figure 5 CFRP specimen 2.1, transient test, before and after the test.

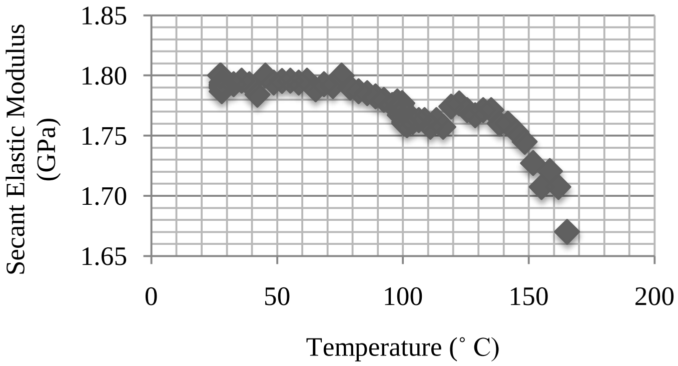

Figure 6 Secant modulus for specimen 2.1 vs. temperature.

7 FULL-SCALE FIRE EXPERIMENTS

Two beams were constructed as a part of ongoing research on structural behaviour of FRP strengthened members in fire. The steel reinforced concrete beams were 3900 mm long and 400 mm deep with a 1220 mm wide flange (150 mm thick) and a 300 mm wide web. These T-beams were strengthened with external FRP, and fire protection for the FRP was provided by sprayed insulation. These beams were then exposed to a standard ASTM fire while under sustained loading. FOS were attached to longitudinal steel bars to capture temperature and strain during the fire test of the beams (Figure 7). Figure 8-a shows the condition of beam after four hours of exposure to standard fire. Both beams successfully resisted the sustained applied load for more than four hours of fire exposure without structural failure. Figure 8-b shows the temperature distribution at the insulation surface, the FRP-insulation interface, and the FRP-concrete interface (concrete surface) at midspan of the T-beam.

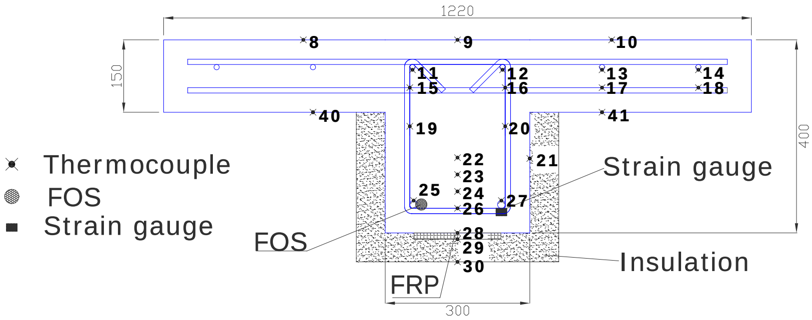

Figure 7 Details of reinforcement and instrumentation for beams (dimensions in mm).

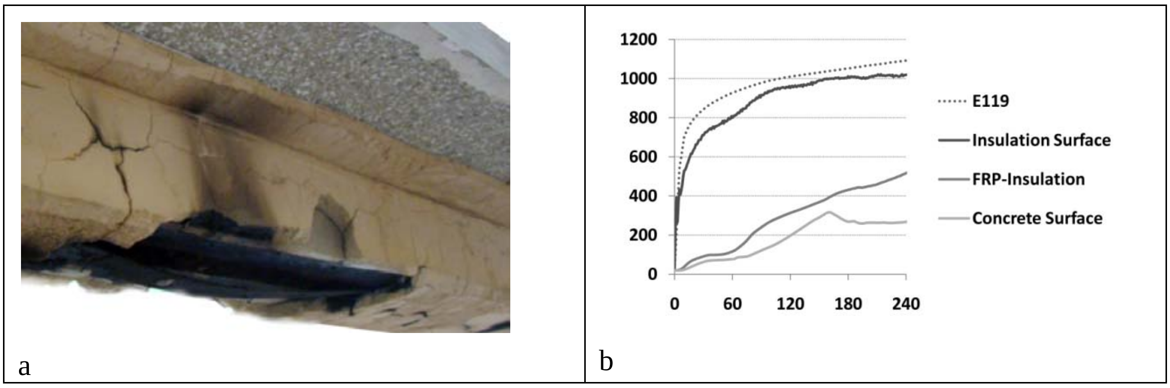

Figure 8 (a) Beams after four hours of exposure to standard fire and (b) Temperature (˚C) vs. exposure time (min) at midspan of the T-beam.

8 CONCLUSIONS

This paper demonstrates various methods of temperature and strain measurement techniques suitable for structural health monitoring. The focus is placed especially on high temperature sensing.

For FRP coupon testing for tensile strength, no significant loss of strength occurred at temperatures below T_g, and the CFRP coupons preserved slightly more than half of their room temperature strength even at temperatures above their T_g. This residual strength exceeds the strength requirements in most flexural strengthening applications provided that adequate bond can be maintained between the FRP and concrete. Further investigations need to be done to provide statistically reliable data on FRP behaviour at elevated temperatures.

Although PIV analysis is a convenient and accurate method of strain measurement, the analysis will not be suitable where the surface texture of the material is damaged.

9 ACKNOWLEDGMENTS

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