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Cover Page

Title:
Performance in fire of fibre reinforced polymer strengthened concrete beams including embedded fibre optic sensors

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ABSTRACT

Fibre reinforced polymer (FRP) materials are increasingly being applied in many areas of construction, particularly for strengthening of concrete beams. However, concerns associated with fire remain an obstacle to applications of FRP materials in buildings and parking garages due to their susceptibility to degradation at elevated temperatures. For FRP strengthened concrete beams, the bond properties of FRP materials at high temperature are critical. Additionally, 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 also discusses the development of technology for fibre optic sensing at high temperatures. 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 will then be exposed to a standard ASTM fire while under sustained loading. This paper also presents an experimental investigation to characterize the bond properties of some currently available FRPs under various loading and thermal regimes ranging from ambient temperature to 200ºC. Lap splice tests are conducted under both steady-state and transient temperature conditions, and the results of the two types of testing are compared.

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INTRODUCTION

Fibre reinforced polymer (FRP) materials are increasingly being applied in many areas of construction, particularly for strengthening of concrete beams. However, concerns associated with fire remain an obstacle to applications of FRP materials in buildings and parking garages due to their susceptibility to degradation at elevated temperatures [1]. Research is being conducted at Queen's University in conjunction with the National Research Council of Canada (NRC) and industry partners to investigate the effects of fire on such FRP strengthened concrete beams [2]. A major portion of the study involves numerical fire endurance modelling. For such models, the bond properties of FRP materials at high temperature are critical.

Additionally, 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 also discusses the development of technology for fibre optic sensing at high temperatures.

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 will then be exposed to a standard ASTM fire while under sustained loading.

This paper also presents an experimental investigation to characterize the bond properties of some currently available FRPs under various loading and thermal regimes ranging from ambient temperature to 200ºC. Lap splice and FRP to concrete bond tests are conducted. Tests are conducted under both steady-state and transient temperature conditions, and the results of the two types of testing are compared and discussed. Results from these tests will also be used to develop analytical models representing the bond behaviour of FRP. Information from these tests will be used in calibrating coupled heat transfer and structural analysis numerical models for FRP strengthened members which are currently being developed at Queen's University.

BACKROUND & RESEARCH SIGNIFICANCE

Very few studies have considered the fire behaviour of externally bonded FRP strengthened beams. Deuring [3] tested six beams (300mm by 400mm by 5m) where four of them were strengthened with carbon FRP (CFRP) plates and some were insulated with fire resistance boards. The un-insulated beams had a fire endurance of 81 minutes while the insulated beams gave an endurance of 146 minutes. Interestingly the endurance of insulated CFRP plated beam was larger than the un-strengthened reinforced concrete beam. Blontrock [4] tested CFRP plated beams using multiple insulation schemes. During his experiments, when the temperature of FRP reached the glass transition temperature, T_g, the load bearing contribution of FRP was significantly reduced. The glass transition temperature is defined as "the midpoint of the temperature range over which an amorphous material (such as glass or a high polymer) changes from (or to) a brittle, vitreous state to (or from) a plastic state" [1]. Williams et al. [2] tested two full-scale insulated T-beams and found that beams with sufficient insulation can achieve fire endurances of more than 4 hours.

EXPERIMENTAL PROGRAM

A two-pronged experimental approach is being taken to address the issue of the performance of FRP strengthened concrete beams in fire. Full-scale fire tests are being conducted on T-beams including specialized high temperature fibre optic sensors. To evaluate the material performance of the FRP, extensive small-scale tests are being carried out to determine the effects of high temperature on bond of FRP.

Full-scale tests

Figure 1 shows the construction details of the T-beams including the internal reinforcement and the location of thermocouples and innovative fibre optic sensors. The beams are 3900 mm long and 400 mm deep with a 1220 mm wide flange (150 mm thick) and a 300 mm wide web. The beams are reinforced in flexure with 2-15 mm diameter steel bars (total area of 400 mm^2) and in shear with 11 mm diameter stirrups (bar area of 100 mm^2). The clear cover to the stirrups is 50 mm giving and effective depth to the flexural reinforcement of 330 mm. The tested 28 day cylinder strength of the concrete was 32 MPa. A Sika CarboDur S812 CFRP plate or 1 layer of Sika Hex 103C sheets (200 mm wide) is planned for flexural strengthening with a 40 mm insulation thickness. The beams will also be strengthened in shear with U-wraps. Table I summarizes the material properties of the FRP.

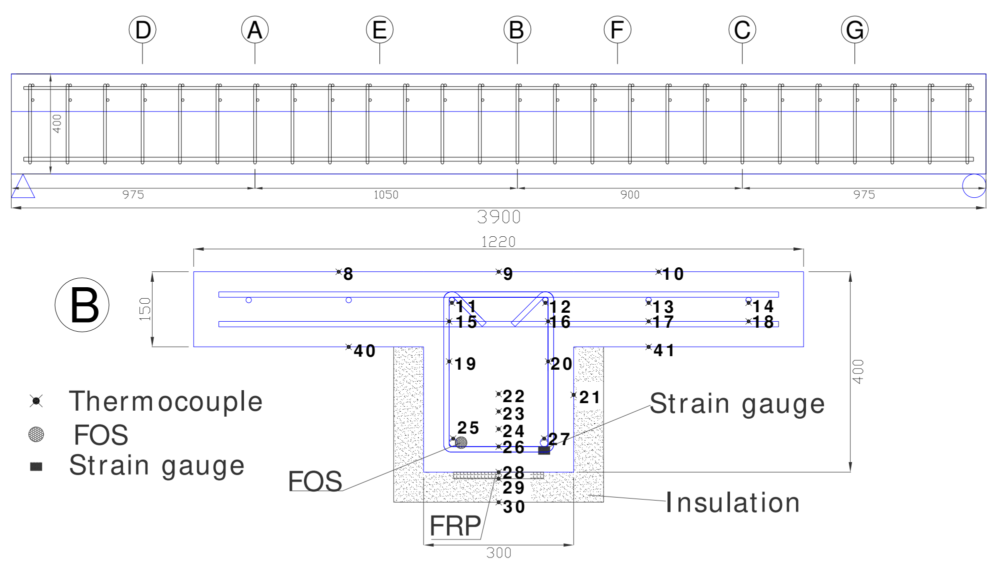


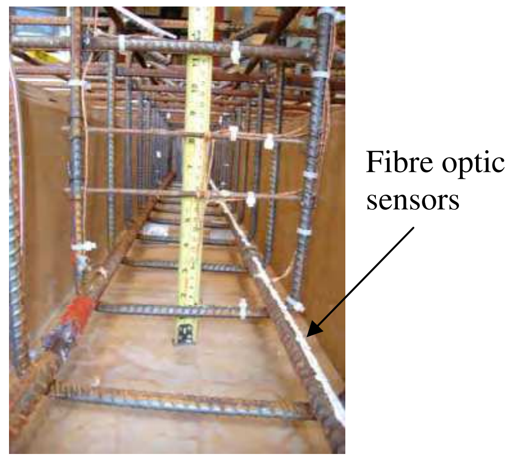
Figure 1: Details of T-beams (dimensions in mm)

TABLE I. MATERIAL PROPERTIES OF FRP

Type of material	Thickness (mm)	Modulus (GPa)	Strength (MPa)	Ultimate strain (%)	T_g (°C)
CarboDur S812 CFRP plate	1.2	165	2800	1.7	150
Sikadur 330 epoxy	–	3.8	30	1.5	60
SikaWrap Hex 103C CFRP sheet	1.0	70.6	849	1.1	60
Sikadur 300 epoxy	–	1.7	55	3.0	60 - 85
Tyfo SCH-41 CFRP sheet	1.0	95.8	968	1.0	75
Tyfo Type S resin	–	3.2	72.4	5.0	75

(a)

(b)



(c)

Figure 2: Installation of fibre optic sensors (a) sensors on reinforcing bar (b) construction of beams (c) sensors shown along length of reinforcing bar in reinforcement cage

The T-beams were also instrumented with specialized high temperature fibre optic sensors as shown in Fig. 2. To protect the fibres from damage, they are attached to reinforcing steel bars as shown in Fig. 2. The high temperature adhesive used to attach the fibre to steel protects the fibres from high alkaline environment of concrete. The distributed fibre-optic sensing system is based on Brillouin scattering. Zeng et.al. [5] used Brillouin-based sensors to measure strain in a reinforced concrete beam with a spatial resolution of 500 mm along a 1.65 m long beam. One of the advantages of Brillouin-based sensors is the capability of measuring temperature and strain simultaneously. Zou et al. [6] have reported temperature and strain measurement resolution of 1.3 ±°C and 15 $\mu\varepsilon$ using this type of fibre optic sensors with a spatial resolution of 150 mm. Recently most of the strain sensing using Brillouin scattering sensor has been based on a standard single mode fibre (SMF28) with acrylate coating, which can sustain maximum strain of 1%-1.5% and temperature of 80°C and this limitation is insufficient for many monitoring applications. Recently, novel sensing fibre with carbon/polyimide coating has been emerged for applications in harsh environments. This kind of fibre can sustain a maximum strain of up to 4% and temperature as high as 450°C and becomes idea candidate for monitoring applications at high temperatures.

After strengthening and insulating the beams, they will be fire tested at the National Research Council of Canada in the full scale floor furnace. Table II summarizes the predicted strength of these beams using various North American design provisions. Based on these calculations, the applied load during the fire test will be taken as 31.2 kN/m which corresponds to the full service load for the predicted strength according to CSA S806 [7]. The standard ASTM E119 [8] fire curve will be followed during the test.

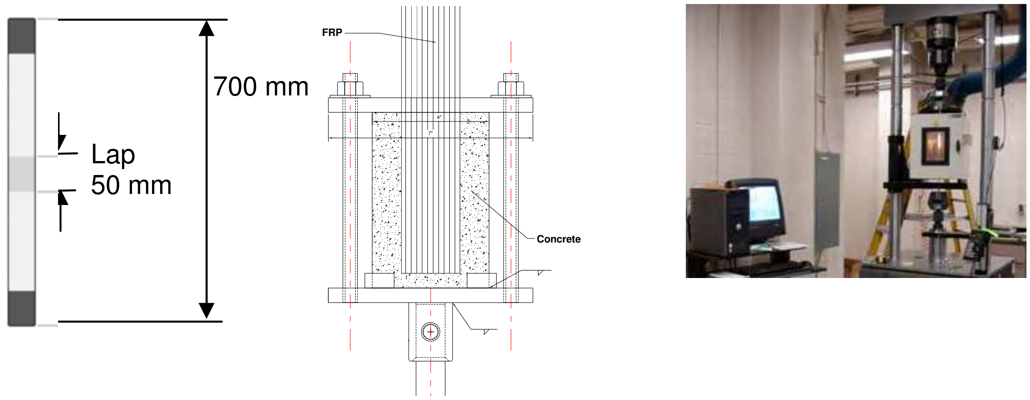
Bond testing

One of the critical elements in the FRP strengthening system is the bond between the FRP and concrete. To better understand the bond performance at high temperatures and in fire situations, material testing is on-going to quantify the bond performance at high temperature of FRP to FRP through lap-splice specimens and between FRP and concrete.

Figure 3 shows the test configurations for testing the lap-splice and FRP to concrete bond. These tests are conducted in an INSTRON Universal Testing Machine (UTM), shown in Fig. 3(c), which has an integrated, custom designed thermal chamber with an internal dimension of 250 mm (width) by 250 mm (depth) by 300 mm (height) and has a maximum load capacity of 600 kN.

TABLE II. PREDICTED STRENGTH FOR BEAM STRENGTHENED WITH CFRP PLATES

CarboDur S812			**Mr**	**increase**	**Mservice D+L**	**wD=wL**	**Vf end**
			kN.m	%	kN.m	**kN/m**	**kN**
ACI 440.2R-08 [1]	Un-strengthened		52.3		37.4	10.3	55.0
	Strengthened	**Debonding**	**70.0**	**33.7%**	**50.0**	**13.8**	**73.5**
		FRP rupture	127.9	144.4%	91.4	25.2	134.5
CSA S806 04 [7]	Un-strengthened		50.2		36.5	10.1	52.8
	Strengthened	**Debonding**	**77.7**	**54.7%**	**56.5**	**15.6**	**81.6**
		FRP rupture	125.5	149.8%	91.2	25.2	131.8
CSA S6 06 [9]	Un-strengthened		53.2		36.7	10.1	55.9
	Strengthened	**Debonding**	**75.7**	**42.3%**	**52.2**	**14.4**	**79.5**
		FRP rupture	128.6	141.8%	88.7	24.5	135.2
Predicted Actual	Un-strengthened		68.1		-	18.8	71.6
	Strengthened		164.5		-	45.4	172.8
	Tension steel yield limit		**53.4**		**-**	**14.7**	**56.1**



(a) (b) (c)

Figure 3: Bond testing configuration (a) Lap-splice (b) FRP to concrete bond (c) test machine

For the purposes of this paper, results are presented for Fibrwrap SCH-41 Carbon Fibre with Type S resin tested in the lap-splice configuration and in tension. Table I presents the properties of these materials. The FRP to concrete bond tests are still in progress and data are not yet available. Both steady-state and transient temperature tests were conducted. For the steady-state tests, the coupons were exposed to a specified temperature and then loaded to failure. For the transient tests, the FRP specimens were subjected to a specified sustained load for 10 minutes under ambient temperature and then heated at 10°C/min until failure. The specimens were loaded to 10%, 20%, 40%, or 70% of their room temperature lap-splice bond strength. No investigation on the heating and loading rate, both of which may be important, has been conducted thus far.

For all levels of temperature, exposure, and sustained load levels, five identical coupons were tested. This number of coupons was chosen as a reasonable minimum number of samples to allow a meaningful statistical comparison of the different treatments. Even with this relatively small number of coupons for each treatment, approximately 100 tests were conducted for the results presented in this paper.

The tension coupons made using carbon fibre experienced notable strength loss at temperatures of 45ºC. The tests reliably suggested that approximately 20% strength was consistently lost after exposure to this temperature. At higher temperatures, beginning at 60ºC the coupons maintained about 45% of their average ambient temperature strength and appeared to retain this strength level up until temperatures of 90ºC. Beyond, at exposure to 200ºC additional strength loss was evident and the coupons retained approximately 34% of their room temperature strength. Tension coupons were also tested in transient conditions. The coupons were loaded to 37% of their ambient temperature ultimate strength and failed at 96ºC with a standard deviation of 14ºC.

For the lap-splice specimens, CFRP coupons retained approximately 80% of their ambient lap-splice strength at 45 ºC. However, at exposure to higher temperatures the CFRP lap-splice coupons had virtually no strength in bond at all. The coupons were reduced to 16% strength at 60ºC and less than 5% of their strength at exposure to temperatures of 90ºC and 200ºC. The CFRP coupons held under sustained load failed at temperatures expected based on the constant temperature tests. The coupons again exhibited a rapid loss of strength at exposure to temperatures above 45ºC. This finding is similar to the preliminary work of Gamage et al. [10]. This research will expand significantly on Gamage's work by considering different types of materials and an extensive number of data points to develop statistically relevant material properties.

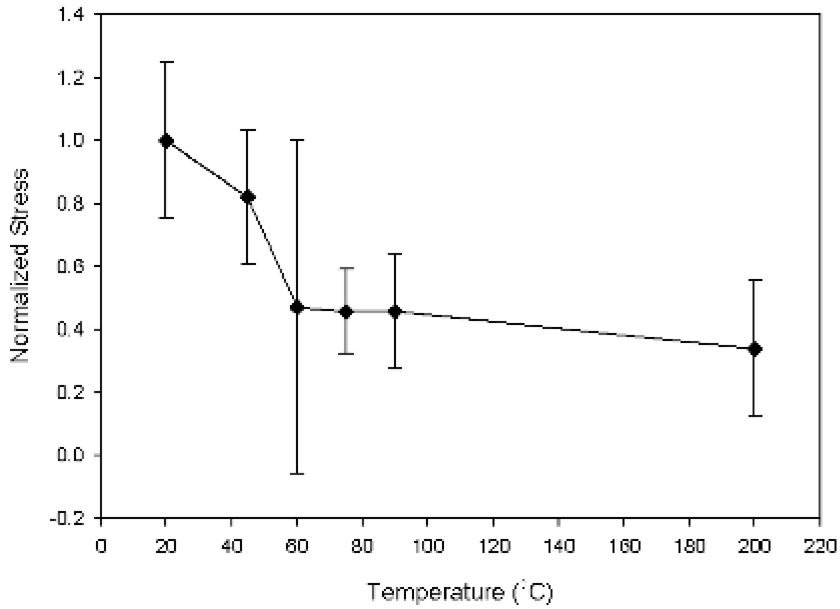


Figure 4: Tensile strength stress of CFRP with S type resin normalized with respect to the room temperature strength

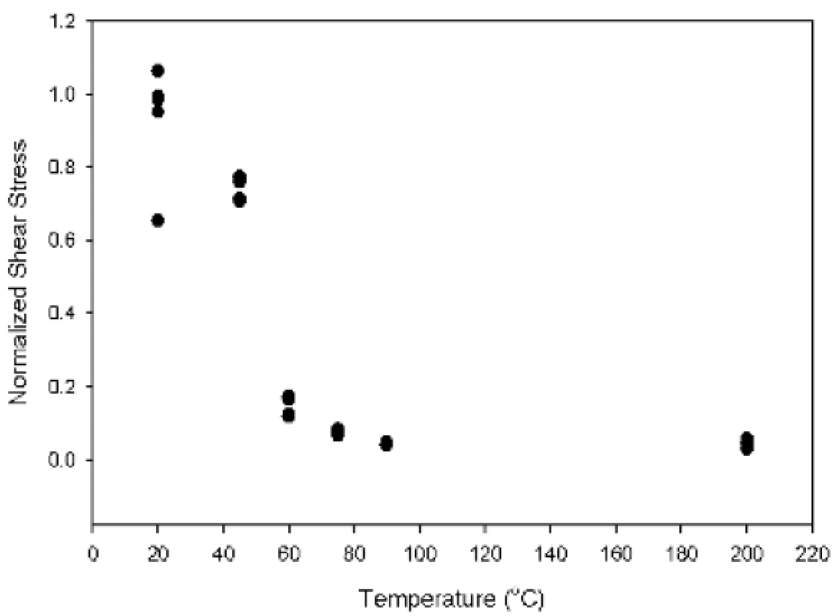


Figure 5: Lap splice bond shear stress of CFRP with S type resin normalized with respect to the room temperature strength

CONCLUSIONS AND RECOMMEDATIONS

This paper discussed testing to evaluate the fire performance of FRP strengthened concrete beams including the development of technology for fibre optic sensing at high temperatures. This paper also presented tests to characterize the material properties of some currently available FRPs up to 200ºC. The CFRP material tested in this paper experienced 55% loss in tensile strength, and 85% loss in FRP lap-splice strength at a temperature of 60°C. Thus, these CFRP materials, with sufficient anchorage, can maintain 40% of their tensile strength at temperatures well in excess of the T_g of their resins. Approximately 90% of the CFRP lap-splice strength was lost at temperatures slightly above T_g. These results should be taken with caution because they represent the most severe possible test of FRP lap-splice strength and are not representative of longer FRP splice lengths used in practice. Thus, more research is required to investigate longer bond lengths and to determine the consequences for member performance in fire.

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REFERENCES

1. ACI, 2008. *ACI 440.2R-08 Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, American Concrete Institute, Farmington Hills, MI.
2. Williams, B.K., V.K.R. Kodur, M.F. Green, and L.A. Bisby. 2008. "Fire Endurance of FRP Strengthened Concrete T-Beams," *ACI Struct. J.,* 105(1): 60-67.
3. Deuring, M. 1994. "Brandversuche an Nachtraglich Verstarkten Tragern aus Beton," Research Report EMPA No. 148,795, Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dubendorf, Switzerland.
4. Blontrock, H., L. Taerwe, and P. Vandevelde. 2000. "Fire Tests on Concrete Beams Strengthened with Fibre Composite Laminates," in *Third PhD Symposium*, Vienna, Austria, 10 pp.
5. Zeng, X., X. Bao, C. Y. Chhoa, T. W. Bremner, A. W. Brown, M. D. DeMerchant, G. Ferrier, A. L. Kalamkarov, and A. V. Georgiades. 2002. "Strain measurement in a concrete beam by use of the Brillouin-scattering-based distributed fiber sensor with single-mode fibers embedded in glass fiber reinforced polymer rods and bonded to steel reinforcing bars," *Appl. Opt.* 41(24): 5105-5114.
6. Zou, L., X. Bao, V. S. Afshar, and L. Chen, 2004. "Dependence of the Brillouin frequency shift on strain and temperature in a photonic crystal fiber," *Optics letters* 29 (13): 1485-1487.
7. CSA, 2002. *CAN/CSA S806-02 Design and Construction of Building Components with Fibre-Reinforced Polymers,* Canadian Standards Association, Mississauga, ON.
8. ASTM, 2001. *ASTM Test Method E119-01: Standard Methods of Fire Test of Building Construction and Materials*, American Society for Testing and Materials, West Conshohocken, PA.
9. CSA, 2006. *CAN/CSA S6-06 Canadian Highway Bridge Design Code*, Canadian Standards Association, Mississauga, ON.
10. Gamage, J.C.P.H. , M.B. Wong, and R. Al-Mahaidi, 2005. "Performance of CFRP Strengthened Concrete Members under Elevated Temperatures," in *Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005),* 7- 9 Dec. Hong Kong, China, pp. 113-118.