High Temperature Residual Properties of Externally-Bonded FRP Systems

by S.K. Foster and L.A. Bisby

Synopsis: The use of externally-bonded FRP plates and sheets to strengthen existing reinforced concrete structures is now widely recognized. However, a primary concern that still discourages the use of FRPs in some cases is their assumed susceptibility to fire. While recent studies have demonstrated that the overall performance of appropriately designed and insulated FRP-strengthened reinforced concrete members is satisfactory, the specific behavior of FRP materials at high temperature and after exposure to high temperature remains largely unknown, particularly for externally-bonded FRP strengthening systems. As a first step in an effort to learn more about the high temperature properties of these systems, an initial series of tests is presented to study the high temperature residual properties of externally-bonded carbon and glass FRP systems for concrete. Axial tension tests, single-lap bond tests, thermogravimetric analysis, and differential scanning calorimetry are all used to elucidate high temperature residual performance. The potential consequences of these initial results for the fire-safe design of FRP-strengthened reinforced concrete members are discussed.

Keywords: fiber-reinforced polymers; fire; high-temperature residual properties; reinforced concrete; strengthening

Sarah K. Foster is a Master of Science student in the Department of Civil Engineering at Queen's University, Canada. She received her B.Sc. in Civil Engineering from Queen's University in 2004. Her current research interests are in the area of strengthening reinforced concrete structures with fiber reinforced polymers (FRPs), with a current emphasis on the behaviour of infrastructure FRPs at high temperature.

Dr. Luke A. Bisby is an Assistant Professor of civil engineering at Queen's University, Canada and a Project Leader in the ISIS Canada Research Network. His research interests include uses of fiber reinforced polymers (FRPs) in structures and the fire behavior of materials and structures. Dr. Bisby is an Associate Member of ACI Committees 440-FRP Reinforcement, and 216-Fire Resistance and Fire Protection of Structures.

INTRODUCTION

Prosperous modern societies depend to a large extent on functional and complex systems of infrastructure. In many countries, such as Canada and the United States of America, these essential infrastructure systems are deteriorating at an alarming rate. Some of the more important factors contributing to this deterioration include corrosion of steel and reinforcing steel, increased service loads, and increasingly severe design requirements. Engineers within the Civil Infrastructure Community have only relatively recently recognized the magnitude of the looming crisis, and dire forecasts as to the sustainability of our infrastructure systems have been made (ASCE, 2003; CSCE, 2003). This widespread and ongoing deterioration, in combination with severe economic constraints and political pressures, is forcing the development of effective and efficient repair and strengthening systems for structures.

In recent years, several repair and strengthening systems specifically for reinforced concrete structures have emerged using externally-bonded fiber reinforced polymers (FRPs). These systems can be used to strengthen concrete beams and slabs in both flexure and shear, to increase the strength and ductility of reinforced concrete columns, or even in improving the performance of structural connections (Teng et al., 2002). To date, however, the majority of field applications of these systems have been in bridges or other exterior structures where fire does not pose a significant risk. This is not true in the case of most buildings, where fire safety considerations are a critical part of the design process. Because FRP materials are combustible, and susceptible to deterioration of mechanical and bond properties at elevated temperature (Bisby et al., 2005b), the behavior of concrete members strengthened with FRP systems during fire must be thoroughly investigated before these systems can be used with confidence in buildings. Indeed, recent research needs papers (Harries et al., 2003; Karbhari et al., 2003) have recognized the need for additional information on the performance of FRP strengthening systems in fire, listing research investigating fire as critical (i.e. cannot move forward without this information) for the future widespread implementation of FRP systems in buildings.

RESEARCH SIGNIFICANCE

In October 2004, a National Science Foundation research needs workshop was held in San Francisco in conjunction with American Concrete Institute Committee 440-FRP Reinforcement and the ISIS Canada Research Network (Porter and Harries, 2005). One session of this workshop focused exclusively on research needs associated with fire and extreme loadings. Among the research needs that were identified in this session, several focused specifically on the performance of FRP materials at, and after exposure to, high temperatures, including:

- the development of fundamental material models for predicting fire resistance of FRP or FRP strengthened members;
- a more complete understanding of the post-fire residual strength of internally or externally FRP reinforced structural members;
- the need for additional experimental data to provide fundamental knowledge of behavior under fire and after fire; and
- the need for additional data on the smoke generation and combustion toxicity hazards associated with the use of FRP materials in structures.

This paper seeks to address, at least in part, all of the above research needs. Various issues associated with the performance of FRP systems in fire were also noted in workshop sessions on internal FRP reinforcement for concrete, external FRP reinforcement for concrete, durability of FRP materials, and hybrids and advanced materials. It is thus clear that information in this area is required.

The paper presents the results of an initial test program conducted to study the residual mechanical and bond properties of externally-bonded FRP strengthening systems for concrete after exposure to elevated temperature. The overarching goal of the current study is to elucidate the high temperature performance of specific FRP systems currently in use such that rational and conservative fire design recommendations can be made with confidence. The paper presents only the results of tension tests on glass and carbon FRP coupons, thermogravimetric analysis (TGA) data, and differential scanning calorimetry (DSC) data.

BACKGROUND

There are a number of concerns associated with the behavior of FRP materials at elevated temperature. At elevated temperatures (i.e. above the glass transition temperature (T_g) of the polymer matrix/adhesive) externally-bonded FRP materials can be expected to display severe reductions in strength, stiffness, and bond properties. This can be attributed to reductions in the mechanical properties of the polymer matrix at these temperatures, which leads to a reduction in the ability of the matrix to transfer forces between the fibers. Thus, for unidirectional composites, the matrix dominated properties such as shear strength and bond strength are expected to be more affected at elevated temperatures. Of course, the inherent combustibility of common organic polymer matrices also leads to concerns associated with the potential for increased smoke generation and flame spread, although these concerns are not discussed in this paper.

Relatively little information is currently available on the fire performance of FRP-strengthened concrete members (i.e. performance at high temperature). Over the past ten years a few experimental studies on FRP-strengthened concrete members during fire have been conducted in Europe (Deuring, 1994; Blontrock et al., 2000, 2001) and, more recently, in Canada (Bisby, 2003; Williams, 2004). Experimental studies in Canada have been coupled with the development of numerical fire simulation models (Bisby et al., 2005a) that can be used to predict the fire endurance of these types of members. However, the studies reported to date have, for the most part, studied the overall performance of FRP-strengthened concrete slabs, beams, and columns and they have not dealt specifically with the high temperature behavior of FRPs themselves. Nor have these studies examined the post-fire residual performance of FRPs after exposure to elevated temperature.

The residual performance of common infrastructure FRPs (i.e. after exposure to high temperature) remains poorly understood. While reductions in strength, stiffness, and bond properties will undoubtedly occur at high temperature (Wang et al., 2003; Katz et al., 1999), it is expected that a significant proportion of this strength will be regained on cooling to room temperature. Only two studies on the residual performance of FRP-strengthened concrete members after exposure to high temperature are available in the literature. Saafi and Romine (2002) studied the residual performance of glass FRP-wrapped concrete cylinders after exposure to elevated temperatures of 90ºC, 180ºC, and 360ºC for 0.5, 1, and 3 hour durations. The temperatures were chosen to be 0.5 T_g, 1 T_g and 2 T_g, with T_g quoted as 180ºC for the FRP system being used. The reader will note that a T_g of 180ºC seems unlikely for the system being used in this study, particularly since the T_g for the same system has been measured in the current study (using differential scanning calorimetry) to be 78ºC (discussed later). In any case, Saafi and Romine (2002) observed axial compressive strength reductions of approximately 15%, 26%, and 47% for the FRP-wrapped cylinders after 3-hour exposures to temperatures of 90ºC, 180ºC, and 360ºC respectively. In a similar study, Cleary et al. (2003) tested glass FRP and aramid FRP-wrapped concrete cylinders in axial compression after exposure to elevated temperatures. They observed reductions in ultimate strength of the wrapped cylinders in the range of 9% and 15% after exposure for 90 minutes at temperatures of 150ºC and 180ºC respectively, but essentially no reduction in strength at 120ºC. The T_g of the resin system used in this study was quoted as 121ºC.

While both of the above studies are instructive in terms of the residual performance of FRP-wrapped concrete cylinders, neither one provides much useful information on the specific performance of the FRP wraps themselves. This information is fundamentally important in understanding the high temperature behavior of these members. Limited studies are also available in the literature on the residual performance of concrete members reinforced internally with FRP bars or tendons. A complete survey of the literature in this area is presented by Bisby et al. (2005b).

More recently, Bisby (2003) and Williams (2004) have presented results of experimental and numerical studies conducted to investigate the fire performance of externally-bonded FRP-strengthening systems for concrete slabs, beams, and columns. These studies suggested that appropriately designed and insulated FRP-strengthened concrete members can achieve satisfactory fire endurances of greater than four hours. However, because the specific performance of the FRP materials at high temperatures was not known in these studies, it remains unclear if, or for how long, the insulated externally-bonded FRP wraps remained effective during fire, and it is thus difficult to use the test data or numerical models that were developed to recommend fire insulation thicknesses that will protect FRP wraps from fire for prescribed durations. While the overall performance of the FRP-strengthened members was shown to be satisfactory, the performance of the FRPs remains essentially unknown.

Clearly, it is not currently known what temperature exposures are critical for the fire survivability of common externally-bonded FRP strengthening systems for concrete. It has been suggested in the literature that the glass transition temperature should be taken as the upper allowable temperature limit. However, this criterion is perhaps unnecessarily restrictive in some cases, although it is certainly conservative and defensible until more complete information is available. Before design recommendations to ensure fire survivability of FRP-wrapped concrete members can be formulated, it is essential to more completely understand the high-temperature residual performance of the FRP materials themselves. In concrete FRP strengthening applications, many of which are bond critical, it is important to clearly understand the variations in strength, stiffness, and bond properties with increasing exposure temperature. These issues are all addressed, in part, in the study presented in this paper.

EXPERIMENTAL PROGRAM

The experimental program consists of five different series of tests, namely residual strength tension tests on FRP coupons, residual strength tension tests on single-lap FRP-to-FRP bonds, residual strength pull-apart bond tests on the FRP-to-concrete bond, thermogravimetric analysis (TGA) on FRPs and their individual components, and differential scanning calorimetry (DSC) to determine T_g for the various polymer matrices used. Three different FRP repair systems are being used in the current study as representative systems that are currently in widespread use in industry. Carbon/epoxy and glass/epoxy systems from a single supplier have been selected, as well as an additional carbon/epoxy system from a second supplier. Details of the three FRP systems being studied are included in Table 1. Details of the complete experimental program are given in Tables 2 and 3. This paper presents results to date from Series I, IV, and V, as shown by the shaded cells in Tables 2 and 3.

For Series I tests, FRP coupons were prepared by fabricating sheets of cured FRP systems. The epoxy-saturated fiber sheets were sandwiched between two steel plates to ensure a uniform, smooth surface. Coupons were subsequently cut from the sheet and precision machined, with a tolerance of 0.025mm, to dimensions specified by ACI 440.3R-04 (ACI, 2004).

Thermal exposures were accomplished by placing the coupons in a programmable electric muffle furnace and heating to the desired temperature. A constant temperature was maintained for three hours, after which the furnace was turned off and allowed to cool slowly to room temperature. This temperature regime was chosen to simulate temperatures that might be experienced by an insulated FRP system in an actual fire situation, based on previous testing on full-scale FRP-strengthened and insulated reinforced concrete members (Bisby et al., 2005c). Figure 1 shows typical temperature profiles recorded for the FRP coupons tested to date. Once the specimens had cooled to room temperature, prefabricated glass FRP tabs were bonded to their ends to prevent grip failure during testing. Preliminary testing with this gripping system showed grip failure to be uncommon. Figure 2 shows a schematic of the coupon specimens.

The FRP coupons were tested in tension using a universal testing machine with non-hydraulic wedge-action grips. An extensometer was used to record strains to be used in determining the elastic modulus; it was removed at 3000 microstrain as specified by ACI (2004). Foil strain gauges were also used on one specimen per exposure group to verify the accuracy of the extensometer and to record the complete stress-strain response.

Series IV tests consisted of TGA to determine the temperature at which the epoxy polymer matrix began to burn off, signifying severe and irreversible chemical decomposition and loss of the matrices' mechanical properties. Series V tests consisted of DSC to determine the T_g of the polymer matrix used. The TGA and DSC studies were conducted according to ASTM E2105 (ASTM, 2000) and ASTM D3418 (ASTM, 2003), respectively, using a TA Instruments TGA Q500 thermogravimetric analyzer and a TA Instruments DSC Q100 differential scanning calorimeter.

EXPERIMENTAL RESULTS AND ANALYSIS

The results of Series IV tests are shown in Figure 3. The epoxy, CFRP 1, and GFRP specimens all experienced major reductions in mass centered at a temperature of 367°C. This can be attributed to the burning off of the epoxy in the range of these decomposition temperatures. The specimens consisting of pure carbon fibers and glass fibers showed virtually no reduction in mass within the same temperature range, indicating that the fibers do not experience any significant thermal decomposition at the temperature exposures to which they were subjected. Based on the results of the TGA it is expected that there should not be any significant change in the residual tensile strength of the coupons at temperature exposures of less than about 350°C. Indeed, since the fibers appear to be relatively insensitive to temperatures up to at least 600°C, the unidirectional coupons should experience only minor reductions in strength even above 350°C.

In the Series V testing, the glass transition temperature was determined to be approximately 78°C for Epoxy 1. The reader should note that this value is based on resin samples that were cured at room temperature, as would be the case in a field application of an externally-bonded FRP strengthening system. The T_g is significantly lower than the decomposition temperatures observed in the Series IV tests and noted previously. It is not clear at present how exposure to temperatures in excess of T_g affects the residual performance of infrastructure FRPs. It is expected, for unidirectional FRPs like those considered herein, that exceeding the T_g will not severely affect the residual tensile strength in the fiber direction (although it may affect residual bond performance, which is also being studied as part of the current project).

The results of Series I tests are shown in Figures 4 through 11. During heating, the distinct odour of burning epoxy was evident in all tests, even at 100°C exposures, indicating some decomposition of the polymer matrix. Specimens exposed to 100°C did not exhibit any change in colour, although they did exhibit small residual deformations, likely due to differential shrinkage between the fibers and the polymer matrix. Deformations became more severe as temperature exposures increased. Specimens exposed to 200°C and higher temperatures changed colour, with the magnitude of the colour change proportional to the exposure temperature (refer to Figures 10 and 11). Clearly, the colour change can be attributed to thermal decomposition of the epoxy. After exposure to 400°C, it was observed for all specimen groups that most of the epoxy polymer matrix had burned off, as should be expected given the results of TGA presented earlier. Only a brittle black residual char remained, which weakly held the fibers together.

Stress versus strain curves for one coupon specimen in each exposure group are shown in Figures 4 and 5. From these plots it is evident that there is no obvious change in stress strain behaviour up to exposure temperatures of 300°C. However, at 400°C there appears to be a reduction in both strength and modulus for both glass and carbon FRPs. These observations are supported by the ultimate stress and elastic modulus results from all coupons as shown in Figures 6 through 9. Figure 6 shows that the tensile strengths for the CFRP 1 specimens show no obvious reduction with temperature up to 300°C, but that there are severe reductions at 400°C. Similar observations can be made of the ultimate strength data for GFRP (Figure 7), although it appears that small reductions in strength might be occurring at exposure temperatures as low as 200°C.

Figure 8 shows that CFRP 1 specimens did not show a major reduction in tensile elastic modulus with increasing temperature, but that the variability in the test data increased markedly as the exposure temperature increased. Figure 9 indicates that the GFRP specimens exhibit a reduced tensile elastic modulus above 300°C. These results indicate that, even for unidirectional FRPs with fibers that are relatively insensitive to the effects of elevated temperatures – typical glass and carbon fibers are both essentially insensitive to temperatures up to at least 400°C (Bisby, 2003) – strength and stiffness degradation are observed when these materials are exposed to temperatures that cause significant thermal decomposition of the polymer matrix. The glass transition temperature does not appear to be a significant parameter with respect to the pure tensile strength and stiffness of these materials.

An analysis of variance (ANOVA) was performed on each exposure group's tensile strength data to determine if there was any statistically significant reduction in residual strength. Without including the details of the analysis, except to state that a confidence interval of 95% was selected, the ANOVA concluded that the CFRP 1 specimens did not experience any significant loss in residual strength after an exposure of 300 degrees, but that a significant reduction was observed at 400°C, as is visually evident in Figure 6. The GFRP specimens, however, experienced statistically significant reductions in strength after exposures of 200, 300, and 400°C. The results of the ANOVA are given in Table 4.

CONSEQUENCES FOR RESIDUAL PERFORMANCE OF FRP-STRENGTHENED CONCRETE MEMBERS

Recent research conducted at Queen's University and the National Research Council of Canada (Bisby, 2003; Williams, 2004) has resulted in the development of validated numerical models to simulate the heat transfer behaviour within insulated FRP-strengthened reinforced concrete slabs, beams, and columns. These models, developed and validated in conjunction with full-scale fire endurance tests on these types of members, are capable of predicting the temperatures experienced by insulated externally-bonded FRP strengthening systems during exposure to a standard fire (ASTM, 2001; CAN/ULC, 1989).

For the purposes of illustration only, it is interesting to consider the consequences of allowing FRP temperatures up to 350°C (close to the decomposition temperature of the epoxy polymer matrix) as opposed to the more commonly stated limit of T_g (78°C or 82°C in this case). Based on the full-scale fire testing of Bisby et al. (2005c) and the numerical modeling of Bisby et al. (2005a) for insulated FRP-wrapped 16-inch circular reinforced concrete columns exposed to the standard fire, Figure 12 shows times of fire exposure required to exceed allowable temperature limits for an insulated FRP-wrapped reinforced concrete column. The reader should note that this figure assumes a specific spray-applied cementitious insulation system used previously by Bisby (2003) and Bisby et al. (2005a, 2005c) for thermal protection of FRP wraps in full-scale fire tests for FRP-wrapped reinforced concrete columns. Additional information on the insulation system is presented by Bisby et al. (2005c).

Figure 12 shows, for instance, that the temperature at the level of the FRP wrap for an FRP-wrapped concrete column with 20 mm of insulation would exceed T_g in approximately 20 minutes, whereas the higher thermal decomposition limit of 350°C would be exceeded in 240 minutes (4 hours). Clearly, this suggests that if temperatures greater than T_g are permissible in fire, as the test results presented previously appear to indicate for FRP strengthening applications that are not bond critical, much smaller thicknesses of supplemental insulation may be allowable for FRP-strengthened concrete members (and their residual performance may be much better than currently thought). Additional research and analysis is required before these test results can relied on with confidence in design situations. It is important to recognize that performance of a structural member during fire depends on many factors. Performance during fire depends predominantly on any insulation present and its effects on the concrete and reinforcing steel in the column. Thus, during fire, the FRP properties play only a very small role in influencing fire performance.

SUMMARY AND CONCLUSIONS

Based on the results of the testing presented in this paper, the following conclusions can be drawn:

- Information on the high temperature and residual properties of FRPs used in infrastructure applications is extremely scarce. More complete information on the high-temperature behaviour of these materials is required before rational, conservative, and efficient fire-safety guidelines and insulation schemes can be formulated for FRP-strengthened reinforced concrete members.

- For the externally-bonded FRP system tested in the current study, severe reductions in residual tensile strength and stiffness are observed only at temperatures exceeding the thermal decomposition temperature of the epoxy polymer matrix.

- For the externally-bonded FRP system tested in the current study, exposure temperatures greater than the glass transition temperature of the epoxy polymer matrix do not appear to significantly affect the residual tensile strength or stiffness.

- In applications of externally-bonded FRP repair systems that are not bond critical, exposure temperatures of up to 300ºC are permissible for satisfactory residual performance of the FRP system. Performance at high temperature and performance of bond critical FRP strengthening applications requires further investigation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and Queen's University at Kingston, Canada. The authors would also like to thank Mr. Ed Fyfe at Fyfe Company LLC and Mr. Will Gold at Degussa Building Systems for supplying the FRP materials tested in this study.

REFERENCES

ACI (2004) Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures, ACI 440.3R-04, American Concrete Institute. 40 pp.

ASCE (2003) Report Card for America’s Infrastructure – 2003 Progress Report, American Society of Civil Engineers, http://www.asce.org/reportcard/, accessed February 21, 2005.

ASTM (2003) Standard Test Method for Transition Temperatures of Polymers by Differential Scanning Calorimetry, Test Method D3418-03, American Society for Testing and Materials. 7 pp.

ASTM (2001) Standard Methods of Fire Test of Building Construction and Materials, Test Method E119-01, American Society for Testing and Materials. 21 pp.

ASTM (2000) Standard Practice for General Techniques of Thermogravimetric Analysis (TGA), Test Method E2105-00, American Society for Testing and Materials. 9 pp.

Bisby, L.A. (2003) Fire behaviour of FRP reinforced or confined concrete. PhD thesis, Department of Civil Engineering, Queen's University, Kingston, Canada. 371 pp.

Bisby, L.A., Green, M.F. and Kodur, V.K.R. (2005a) Modeling the behavior of fiber reinforced polymer-confined concrete columns exposed to fire, Journal of Composites for Construction, 9(1), pp. 15-24.

Bisby, L.A., Green, M.F. and Kodur, V.K.R. (2005b) Response to fire of concrete structures that incorporate FRP, accepted, Progress in Structural Engineering and Materials. 10 pp.

Bisby, L.A., Green, M.F. and Kodur, V.K.R. (2005c) Fire endurance of FRP-confined concrete columns, accepted, ACI Structural Journal. 10 pp.

Blontrock, H., Taerwe, L. and Vandevelde, P. (2000) Fire tests on concrete beams strengthened with fibre composite laminates, Third Ph.D. Symposium, Vienna.

Blontrock, H., Taerwe, L. and Vandevelde, P. (2001) Fire testing of concrete slabs strengthened with fibre composite laminates, Proceedings, 5th Annual Symposium on Fibre-Reinforced-Plastic Reinforcement for Concrete Structures, Cambridge, UK, July 2001. pp. 547-556.

CAN/ULC (1989) Standard Methods of Fire Endurance Tests of Building Construction and Materials, ULC-S101, Underwriters' Laboratories of Canada. 49 pp.

Cleary, D.B., Cassino, C.D. and Tortorice, R. (2003) Effect of elevated temperature on a fiber composite used to strengthen concrete columns, Journal of Reinforced Plastics and Composites, 22(10), pp. 881-895.

CSCE (2003) Civil Infrastructure Systems Technology Roadmap 2003-2013, Canadian Society for Civil Engineering, http://www.csce.ca/TRM/TRM-Report_english_01.pdf, accessed February 21, 2005.

Deuring, M. (1994) Brandversuche an nachtraglich verstarkten tragern aus beton. Research Report EMPA No. 148'795. Dubendorf: Swiss Federal Laboratories for Materials Testing and Research.

Harries, K., Porter, M., & Busel, J. (2003) FRP Materials and Concrete - Research Needs, Concrete International, 25(10), pp. 69-74.

Karbhari, V.M., Chin, J.W., Hunston, D., Benmokrane, B., Juska, T., Morgan, R., Lesko, J.J., Sorathia, U. and Reynaud, D. (2003) Durability gap analysis for fiber-reinforced composites in civil infrastructure, Journal of Composites for Construction, 7(3), pp. 238-247.

Katz, A., Berman, N., and Bank, L.C. (1999) Effect High Temperature on the Bond Strength of FRP Rebars, Journal of Composites for Construction, 3(2), pp. 73-81.

Porter, M.L. and Harries, K.A. (2005) Workshop on Research in FRP Composites in Concrete Construction, Final Report submitted to the National Science Foundation, March 2005. 36 pp.

Saafi, M. and Romine, P. (2002) Effect of fire on concrete cylinders confined with GFRP. Proceedings, 2nd International Conference on Durability of Fibre Reinforced Polymer (FRP) Composites for Construction, May 2002, Montreal, QC, pp. 512-521.

Teng, J., Chen, J., Smith, S., and Lam, L. (2002) FRP Strengthened RC Structures, Wiley, UK. 245 pp.

Wang, Y.C., Wong, P.M.H., and Kodur, V.K.R. (2003) Mechanical properties of fibre reinforced polymer reinforcing bars at elevated temperatures, Proceedings of the SFPE/ASCE Specialty Conference – Designing Structures for Fire, Baltimore, MD, pp. 11-20.

Williams, B.K. (2004) Fire performance of FRP-strengthened reinforced concrete flexural members, PhD Thesis, Department of Civil Engineering, Queen's University, Kingston, Canada. 389 pp.

Table 1—Selected manufacturer specified properties of FRP and resin/adhesive systems used in the current study

Property	T_g (°C)[9]	Tensile strength (MPa)[9]	Tensile modulus (GPa)[9]	Strain at rupture (%)[9]	Flexural strength (MPa)[9]	Flexural modulus (GPa)[9]	Design thickness (mm)[9]
Matrices/adhesives							
Epoxy 1[1]	82	72.4	3.18	5.0	123.4	3.12	--
Epoxy 2[2]	71	55.2	3.03	3.5	138.0	3.72	--
Dry fiber properties (in fiber direction)							
Carbon 1[3]	--	3970	230	1.7	--	--	--
Carbon 2[4]	--	3800	227	--	--	--	--
Glass[5]	--	3240	72.4	4.5	--	--	--
Gross laminate properties (in fiber direction)							
CFRP 1[6]	--	986	95.8	1.0	--	--	1.0
CFRP 2[7]	--	3800	227	1.7	--	--	1.3
GFRP[8]	--	575	26.1	2.2	--	--	0.175

[1] Tyfo S Epoxy
[2] MBrace Saturant
[3] Tyfo SCH-41 Fabric
[4] MBrace CF130 Fabric
[5] Tyfo SEH-51 Fabric
[6] Tyfo SCH-41 System w/ Tyfo S Epoxy
[7] MBrace CF130 System w/ MBrace Saturant
[8] Tyfo SEH-51 System w/ Tyfo S Epoxy
[9] Information on specimen conditioning and test methods used to obtain various material properties can be obtained from the material manufacturers.

Table 2—Details of the overall experimental program for the current study (shaded cells represent data presented in the current paper)

Test series	Parameters studied	Specimen config.	Type	No. samples	Exposure temp. (°C)	Designation
I	Tensile strength and elastic modulus	Coupon	CFRP 1	5	20	C1-20
				5	100	C1-100
				5	200	C1-200
				5	300	C1-300
				5	400	C1-400
			GFRP	5	20	G-20
				5	100	G-100
				5	200	G-200
				5	300	G-300
				5	400	G-400
			CFRP 2	5	20	C2-20
				5	100	C2-100
				5	200	C2-200
				5	300	C2-300
				5	400	C2-400
II	FRP to FRP bond strength	Single-lap bond shear tests	CFRP 1	5/designation	TBD[1]	TBD[1]
			GFRP	5/designation	TBD[1]	TBD[1]
			CFRP 2	5/designation	TBD[1]	TBD[1]
III	FRP to concrete bond strength	Double-lap pull-apart bond tests	CFRP 1	1/designation	TBD[1]	TBD[1]
			GFRP	1/designation	TBD[1]	TBD[1]
			CFRP 2	1/designation	TBD[1]	TBD[1]

[1] Exposure temperatures will be chosen so as to bracket temperature exposures causing significant reductions in bond strength. Initial exposure temperatures of 20°C and 200°C will be used, and at least five exposure temperatures will be investigated. It is expected that bond strength reductions will be severe after 200°C exposure.

Table 3—Details of ancillary thermal tests performed on FRPs and component materials during the current study (shaded cells represent data presented in the current paper)

Test series	Parameters studied	Test Method	Type
IV	Glass transition temperature	Differential scanning calorimetry	Epoxy 1
			Epoxy 2
V	Mass loss with temperature	Thermo-gravimetric analysis	Epoxy 1
			CFRP 1
			GFRP
			Carbon fibers 1
			Glass fibers
			Epoxy 2
			CFRP 2
			Carbon fibers 2

Table 4—Analysis of variance results for Series I tensile strength data obtained to date

Test Group	Confidence Interval	F	F_{crit}	Significant?
C1-100	95%	0.502876035	5.317655063	No
C1-200	95%	2.106418417	5.317655063	No
C1-300	95%	0.918680287	5.317655063	No
C1-400	95%	71.51223806	5.317655063	Yes
G-100	95%	0.002104279	5.317655063	No
G-200	95%	36.48743269	5.317655063	Yes
G-300	95%	76.23787265	5.317655063	Yes
G-400	95%	1431.121779	5.317655063	Yes

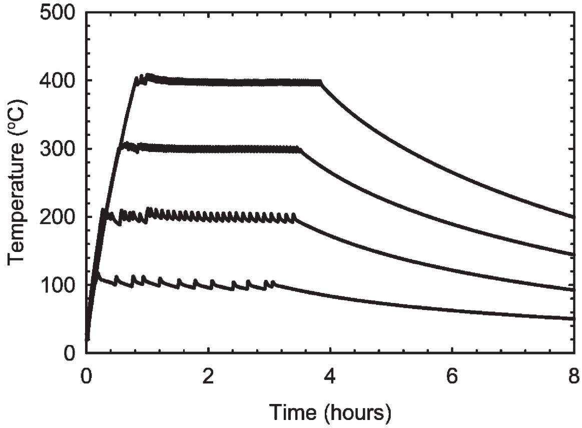

Figure 1—Thermal exposure profiles for coupon samples tested to date.

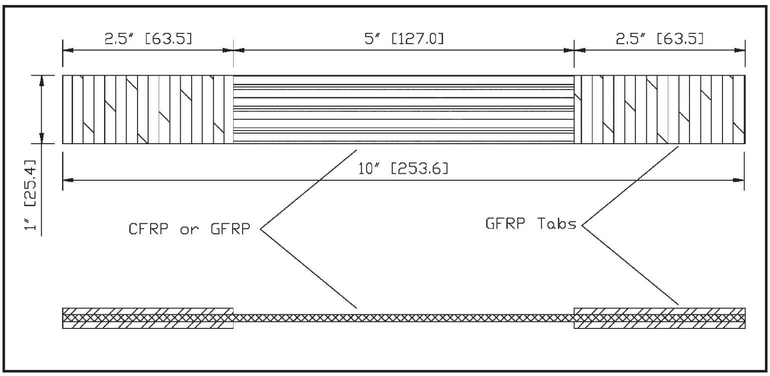

Figure 2—FRP coupon schematic (units in square brackets are mm).

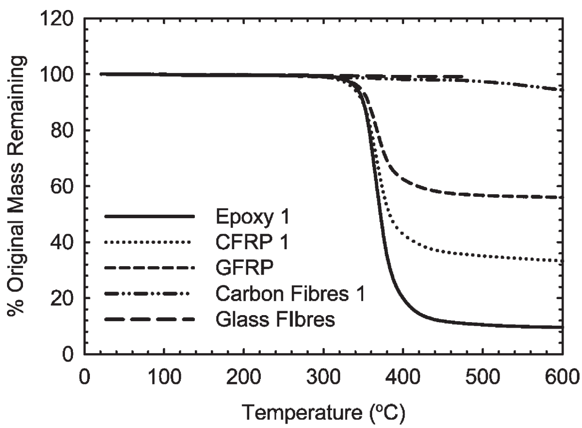

Figure 3—Mass loss with temperature recorded during thermogravimetric analysis of pure Epoxy 1, CFRP 1, GFRP, Carbon Fibers 1, and Glass Fibers.

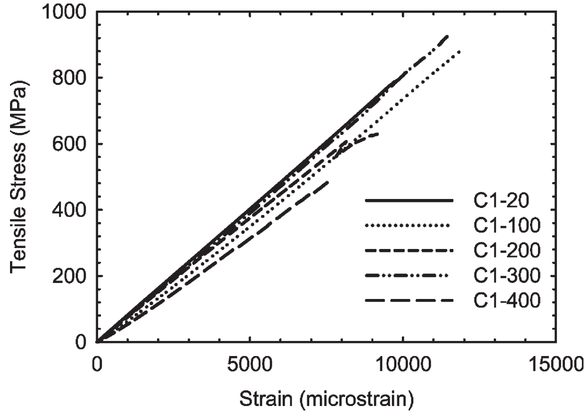

Figure 4—Tensile stress versus strain curves recorded for CFRP 1 coupons after exposure to elevated temperatures.

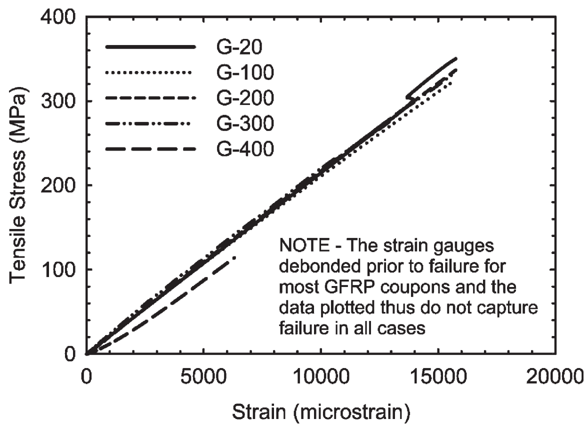

Figure 5—Tensile stress versus strain curves recorded for GFRP coupons after exposure to elevated temperatures.

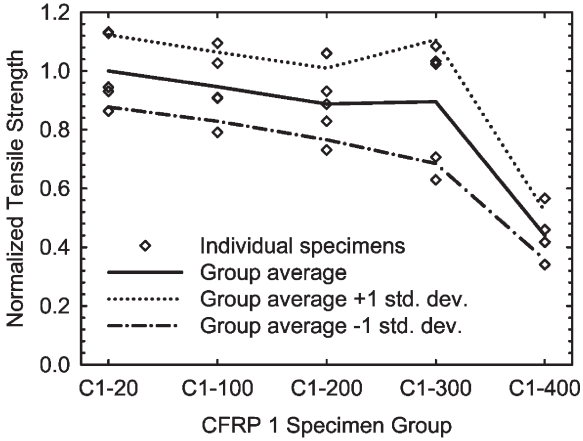

Figure 6—Variation in ultimate tensile strength of CFRP 1 coupons with exposure temperature.

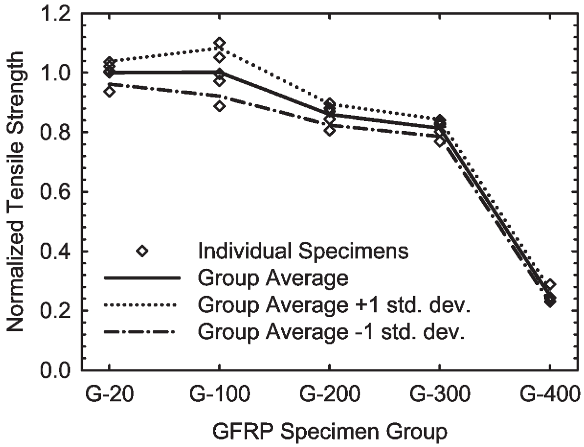

Figure 7—Variation in ultimate tensile strength of GFRP coupons with exposure temperature.

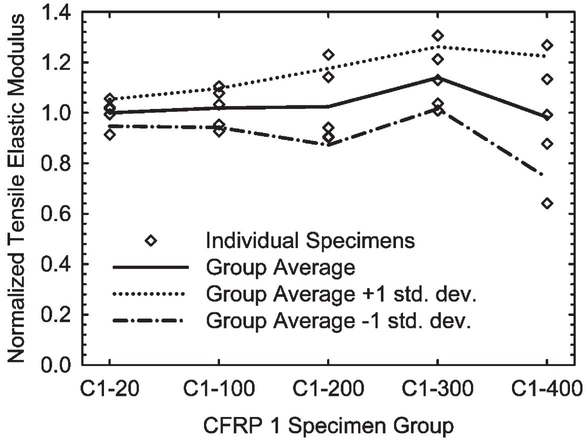

Figure 8—Variation in tensile elastic modulus of CFRP 1 coupons with exposure temperature.

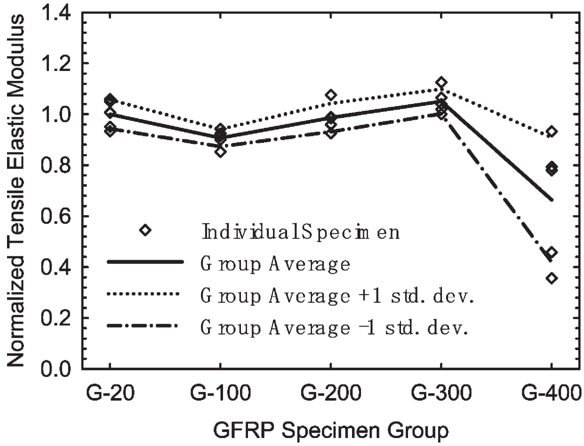

Figure 9—Variation in tensile elastic modulus of GFRP coupons with exposure temperature.

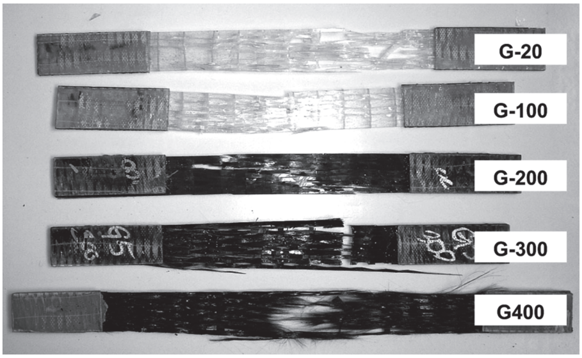

Figure 10—Typical GFRP coupons tested in uniaxial tension after exposure to elevated temperatures.

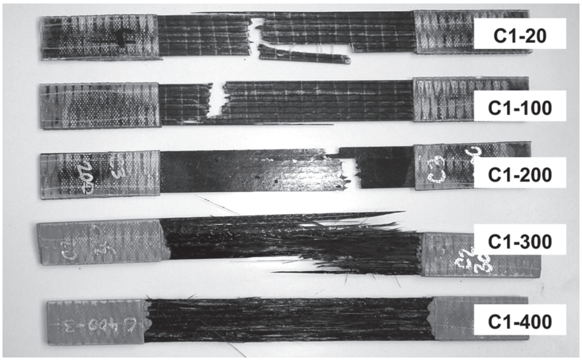

Figure 11—Typical CFRP 1 coupons tested in uniaxial tension after exposure to elevated temperatures.

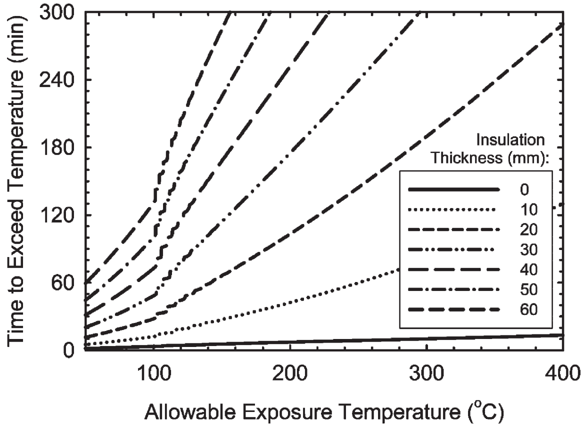

Figure 12—Times of fire exposure required to exceed allowable temperature limits for an insulated FRP-wrapped reinforced concrete column (based on FRP-wrapped column fire tests and numerical analysis presented previously by Bisby (2003)).