IMPROVING FIRE SAFETY OF GLASS FIBRE REINFORCED POLYMERS FOR BRIDGE INFRASTRUCTURES

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ABSTRACT

Civil engineering bridge infrastructure has relied on the use of traditional steel reinforcing materials in concrete structures for decades. There are several disadvantages with these materials related to durability (i.e., corrosion), and as a result, industry is seeking to develop alternative materials. One material being advocated is Glass Fiber Reinforced Polymer (GFRP) which has been suggested as an alternative tensile reinforcement for concrete bridge structures. Bridge infrastructure is critical. As such, we need to consider fire hazards associated with proposed alternative materials. This research examines the high temperature performance of two different types of GFRP tension resisting composite materials: reinforcing bars and stay in place (SIP) form work. Results indicate that while traditional structural fire test methodologies – the high temperature steady state tension test for example – can prescribe suitable design values for GFRP, such experiments may not be readily applicable to examining all relevant and underlying mechanisms which can govern GFRP material behavior in fire. Additional test procedures and investigations into underlying behavior, as have been done by aerospace and marine industries for their composites, may be required to more completely understand the mechanisms which govern fire performance of these materials. Systematic study of those mechanisms can aid the development of GFRP materials and predicate their application in current and future performance based fire designs. The study presents novel insights based on original experiments which may guide future work into development of advanced GFRPs for use in bridges.

INTRODUCTION

Our economies are dependent on functioning and safe bridge infrastructure. Traditional designs include reinforced concrete, which over time can result in high operation and maintenance costs. These costs are mostly due to susceptibility of the reinforcing steel to corrosion and potentially a lack of proper maintenance over time. In response, industry has been proposing the composite material, Glass Fiber Reinforced Polymer (GFRP) as an alternative to traditional tensile reinforcing steel. GFRPs are comprised of micro-scale glass fibers embedded in a polymer (proprietary) resin. This construction material is typically manufactured with a pultrusion process which can shape it into structural sections or tensile reinforcement bars. GFRP is not a new material; the aerospace and marine industries have used these composites for some time; however as they have begun to realize, they come at a high cost. With continual material development, not only will performance improve, but the economics of using the material can be further established. GFRP's high strength, light weight and low susceptibility to corrosion drive its development as an alternative tensile reinforcement in lieu of steel for concrete bridge infrastructure. Numerous research programs currently demonstrate that GFRP materials can provide enhanced durability to concrete bridge infrastructure at ambient temperature. However, few are underway which consider the behavior of GFRP in fire [1, 2]. The fire safety of bridge infrastructure is of importance and must be addressed with continued research [3].

BACKGROUND AND MOTIVATION

When GFRPs are considered for in-fire performance in structural systems (exposed or protected), the acceptable strength loss has been estimated through steady state heated tensile tests (heat then load), and a critical temperature defined in a similar prescriptive manner as has been done for reinforcing steel. Since the purpose of the material is the same a comparison is done 'like for like' through a classic strength test. However, GFRP do not have grain structures that change with temperature like steel; rather, GFRP are characterized by glass transitions where, with increasing temperatures, they begin to soften and experience polymer matrix decomposition and pyrolysis, and under the right conditions can even contribute to the growth of a fire. Thus in order to study the underlying mechanisms and improve this material in the most economical, fire-safe and environmentally friendly way, research beyond the traditional steady state heated tensile test should be pursued; this is particularly important to develop merits and tradeoffs in performance based fire design (PBFD) for this material as well. There are only limited (though informative) investigations of mechanisms underlying the structural behavior of GFRP composites in fire [1, 2, 3]. Herein, the high temperature performance of several types of GFRP from industry manufacturers are examined via a variety of testing regimes which illustrate the complexities associated with their behavior. The research focusses on GFRP composites which could be proposed for use as tensile reinforcement in critical bridge infrastructure: either as structural plate sections for stay-in-place (SIP) form work that is exposed as a bridge deck soffit; or as reinforcing bars that would be embedded in the concrete bridge deck. The results from a combination of material tests including tensile testing with more advanced image based correlation techniques for deformation, cone calorimetry, and environmental scanning electron microscopy, are presented and discussed in this paper. For proprietary reasons, manufacturers have contributed their materials on the basis of anonymity. It should be noted there is a lack of publication of research studies undertaken by many GFRP manufacturers (anonymous and declared). Where data is published, it is often focused on demonstrating that one product meets a set of standards, rather than on studying the mechanisms underlying the fire performance of GFRP. The overarching goal of this paper is to present the reader with the complexity associated with high temperature performance of this material, and encourage deeper investigation into the underlying mechanisms and fire performance of these materials in hopes of further development for broad industry use and creation of standards for testing structural GFRPs.

METHODOLOGY

Materials

A pultrusion process is used to shape GFRP stay-in-place (SIP) formwork into a structural section. In concrete bridges the material serves as tensile reinforcement and as form work. This is a composite reinforcing material in the bridge deck and remains exposed to elements as it also acts as the bridge's soffit. The sections used in this research have an ultimate tensile strength of 350 MPa at ambient temperature. Samples were chosen on the basis of what manufacturers typically supply to the construction industry in North America. All samples were cut to a square area of 100 mm x 100 mm, with coupons also cut for future tensile testing (not discussed herein). Samples and their material configurations are tabulated in Table 1. Samples are referred to as xAy, where 'x' is the sample type, and 'y' is the sample number. Where possible two of each type were considered. Configurations of the materials varied: resin types were polyester or vinylester, sample thickness ranged from 3.6 to 9.5 mm, and fire retardants were contained in some samples. All samples had a maximum 80% (by mass) glass fiber content. The fire retardant compositions were not given to the authors but samples with and without fire retardants were identified. The number of samples was limited to the amount of material given to the researchers in kind. The composite GFRP reinforcing bars considered had a cross-sectional area of approximately 200 mm^2 and a thin epoxy-sand coating. Six samples were prepared and were all cut to 1.5 m in length following a preparation introduced elsewhere [1]. All bars utilized a vinylester resin with an approximate 80% (by mass) fiber content, similar to one of the SIP samples. Ambient tensile strengths were specified at 1700 MPa, though in practice bars are typically loaded in service much below 30% ambient strength to reduce creep effects.

Test Program

Seven tests were performed on four unique SIP sample types. As the application of this type of SIP would be as a soffit to a bridge deck it is important to understand the reaction to fire (flammability, smoke constituents, mass loss rate, etc.) of these samples prior to testing for their mechanical performance. In this study, fire performance characteristics were assessed using a cone calorimeter. Tests were conducted according to ASTM E1354-16 [4] under exposure to a calibrated incident heat flux of 50 KW/m^2 from above. Tests were continued until natural flame extinguishment (flame out) of the sample (post flaming and smoldering was not considered herein). The heating severity used is commonly considered representative of a severe exposure in a standard fire and permits the comparison of the present results to observations reported for commonly tested composite polymers elsewhere. Table 2 details testing configurations for the GFRP bars. All tension tests utilized an Instron Servo-hydraulic frame coupled with a heating chamber. The chamber had a viewing window capable of utilizing high resolution digital image correlation (DIC) techniques for quantitative and qualitative deformation characterization [5]. Images were taken during tensile testing at high temperature and then were sequenced so that deformation could be measured using GeoPIV 8 software. Samples were heated approximately 30% of their length. Testing utilized both steady (heat then load) and transient (load then heat) regimes to enable investigation of the decomposition behavior of the polymer resins under load at high temperature. The heating rate was chosen to be representative of the anticipated rate of heating of an embedded reinforcing bar in concrete heated under the standard fire. Transient testing of GFRP bars is not frequently utilized by researchers; however, showed significant promise in recent GFRP studies [1, 2, 3]. Here, when combined with steady tests and DIC, the procedure enables insights into mechanisms underlying the behavior of the bars.

Table 1. GFRP SIP Test Configurations and Selected Fire Reaction Polymer Test Results with 50Kw/m^2 incident heat flux

Sample	Test Configurations			Test Results			
	Resin Type	Fire Retardant	Thickness (mm)	Ignition Time (s)	Flameout Time (s)	Mass at Ignition (g)	Mass after Flameout (g)
1A		No [a]	3.6	72	410	77.8	55.3
				67	423	76.9	55.2
1B	Polyester	No [a]	9.5	187	1091	180.0	129.2
2A		Yes	6.1	80	671	111.0	73.1
				97	619	110.7	72.2
3A	Vinylester	Yes	4.1	86	300	62.5	38.5
				109	411	60.1	36.5

[a] - manufacturer did not specify

Table 2. GFRP Tensile Bar Test Configurations

Test number	Heating rate (C/min)	Loading level to capacity (%)	Test type	Number of tests
1C	5	33	Transient	2
2C	5 [b]	-	Steady	2
3C	2	33	Transient	1
4C	5	25	Transient	1

[b] - heated to a soak temperature of 400C for 15 minutes, then load applied until failure.

EXPERIMENTAL RESULTS

Stay in place form work (SIP)

A range of SIP materials were assessed for fire reaction properties using the cone calorimeter prior to mechanical testing (which will be considered in future by the authors). Since SIP bridge infrastructure is exposed from below in practice, this was to assess the potential for flame spread even from a localised fire source. Table 1 illustrates selected results taken from each cone test. Some results are not strictly comparable as the thickness and density of the samples differ. Therefore comparative analysis should be interpreted with caution from a structural point of view. Tested sample types exhibited good repeatability. From 'ignition' to 'flame out' all samples illustrated approximately 29 to 39% mass loss predominately from resin decomposition with remaining glass fibres and residual charring accounting for the remaining amounts. This is near the 80% expected fibre content noted by the manufacturers. All samples exhibited a similar delay between exposure and ignition - ignition time – whether or not the manufacturer had specified the addition of a fire retardant.

Sample 1B, also the thickest sample, had the largest delay to ignition which was unexpected due to the suggestion by manufacturer that samples 1A and 1B did not contain fire retardants. The samples (1A and 1B) were therefore assessed independently using SEM microstructural analysis (with energy dispersive spectroscopy), since this is a common initial step to identifying fire retardants though it is also usually followed by FTIR and high performance liquid chromatography analysis [6]. The analysis indicated that indeed, they may have contained an active agent, hypothesized as an Aluminum Trihydoxide filler. Figure 1 illustrates the evolution of Heat Release Rate (HRR) with time for each of the materials tested (repeats not shown). The HRR is an important parameter when discussing the possibilities for flame spread and modelling endeavours. The ‘troughs’ in HRR observed in Figure 1 are due to the woven glass fibres in the resin. Pockets of resin rich material periodically contribute higher amounts of volatiles during their decomposition thus leading to the peaks in HRR seen in Figure 1. As expected, samples 2A and 3A which were known to contain fire retardant additives exhibited lower values of peak HRR. Woven fibre distributions with a discrete char layer on the exposed surfaces were left after burning all samples.

Figure 1
Fire Reaction Properties of GFRP stay in place plates: Heat Release Rate.

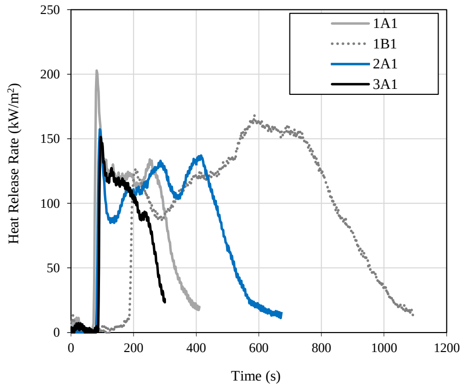
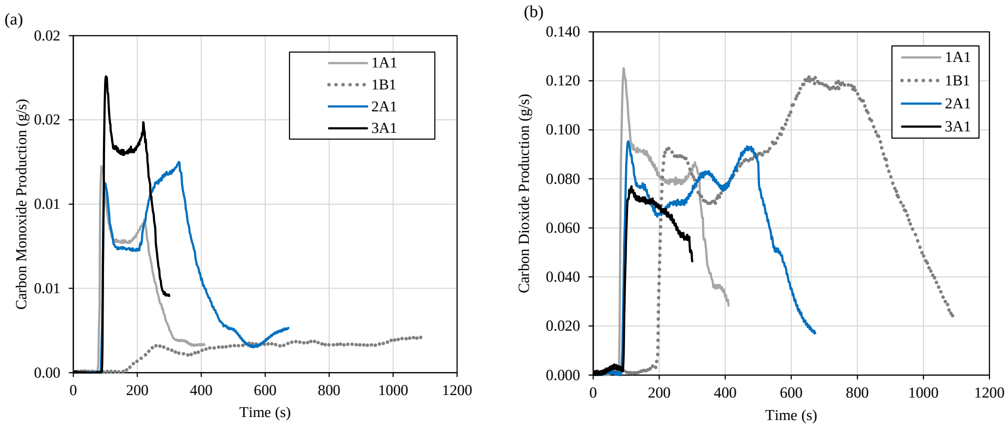


Figure 2
Fire Reaction Properties of GFRP stay in place plates: (a) CO and (b) CO2.

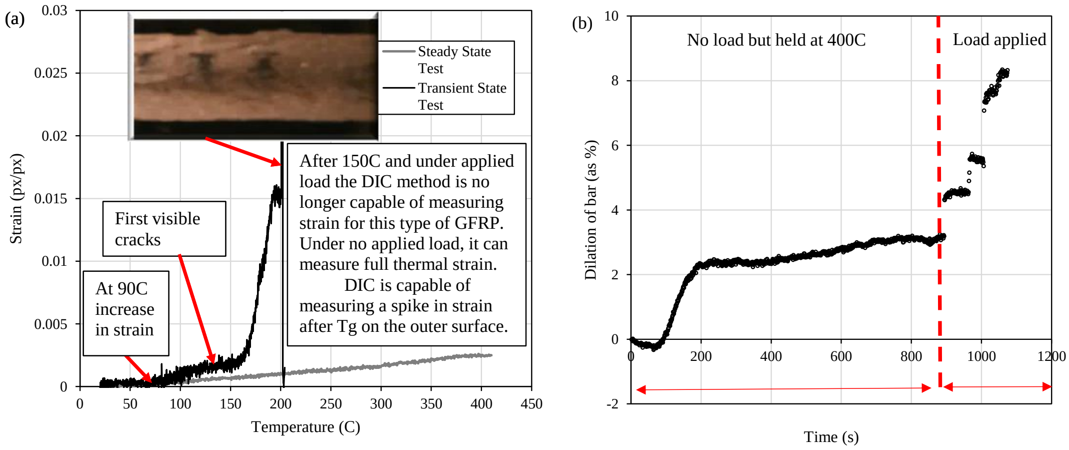


A small SIP sample of approximate thickness 4 mm is not likely to be able to carry the substantial loading seen necessary for bridge structures, however in common practice and for ambient performance assessment of GFRPs, small thickness samples can be used as starting points in mechanical bench scale tests. Those results are often ‘scaled up’ to more realistically sized specimens. In determining fire performance of GFRPs, that procedure is not applicable as a small sample is not necessarily scalable to represent a thick sample. In the present case, all SIP ‘A’ samples exhibited similar CO and CO_2 production rates as shown in Table 2. In contrast, a small production rate of CO was observed for sample ‘B’ in comparison, though all samples demonstrated similar CO_2 production rates. The heat transfer, vaporization and fire chemistry of a sample will change as it becomes ‘thermally’ thick (Sample 1B) since there is often an increase in the bulk thermal capacity of the thicker material which can increase the time to ignition as well as to change the time necessary to heat the resin to its decomposition temperature. This may partially explain the long ignition time for sample 1B as well. Further, since decomposition is also related to thickness, this may have implications for when samples are tested mechanically in tension at different heating rates, and different sizes (see below). In analyzing the present results, consideration should be made that only one sample of 1B was tested; further samples should be analyzed chemically and tested to confirm the present observations.

Tensile reinforcing GFRP bars

Improved DIC techniques and testing procedures (with advanced leveling and higher frequency and resolution of imaging) were employed to observe deformation and study the tensile behavior of GFRP bars at high temperature to inform decomposition theories. Selected results in Figure 3a show differences in effects of the glass transition temperature (Tg) in a steady state and transient tensile test. As the transient test bar approaches about 90C, a slight peak in strain can be observed. Photos from the test at this stage did not show any visible damage on the bar. Once the bar reaches 150C a rapid climb in strain is measured. This correlates to when visible damage - discrete fiber rupturing through the sand layer - can be seen externally on the bar. Such damage is realistic to what could be expected in real fire conditions where reinforcement will be heated under a sustained load. In the steady state test, no increase in strain is observed during this period. After reaching a target temperature of 400C, the temperature of the bar is held constant. In Figure 3b, a linear increase in strain can be observed after 240 seconds of heating and, based on measurements of dilation the bar, appears to expand linearly during this time as well. As load begins to be applied (at 8% bar dilation), DIC methods can no longer measure deformations accurately as the surface texture changes too much too quickly as thermal decomposition processes extend deeper in toward the core of the bar.

Figure 3
Mechanical observations of GFRP bar (a) steady state and Transient tensile tests (b) soak time of steady state test at 400C.



Although a heating soak time of 15 minutes was specified as is done in steel testing to ensure uniformity of heating in the steady state test, in these GFRP samples, it is not clear that holding temperature constant will ensure a uniform temperature, but instead it may result in further decomposition of the resin (at specific temperatures). The heating rate in transient tensile testing of GFRP bars will then also become significant and tensile testing is likely not enough since the decomposition process may well be dependent on the size of the bar. In this case, fire chemistry of the polymers becomes more important for the structural fire engineer to quantify, especially when conditions may be non-standard such as those which are analyzed in PBFD scenarios.

FUTURE WORK AND PRELIMINARY CONCLUSIONS

The choice of resin is important for GFRPs. A common misconception is that, when exposed to fire, all GFRPs will develop a ‘thick’, porous carbonaceous ‘char’ layer which acts as a thermal barrier (similar to timber) and will delay heating towards the centre of the sample. This notion traces to a case study of the *HMS Cattistock*, a naval ship which caught fire and burned for four hours. That fire was hypothesized to have been compartmentalized because of a thick char layer that developed in the FRP composite lining of the walls [7]. However there are other, less referenced case studies where char layers did not develop in fires [7]. The development of a char layer is related to the resin type, fire retardant additives and sample degradation with high temperature. The marine and aerospace industries have developed a significant understanding of resins that perform well in fires. Poly and vinyl ester based polymer resins, although they can be made at low cost, will show negligible development of a char layer [7]. On first look at the polymer resins considered herein (both bars and SIP) there appeared to be minimal to no effective formation of char. Future studies should be conducted to specifically quantify the impacts of both fire retardant additives and residual char across representative materials. However, development of such resins could prohibitively drive up the costs of GFRP structural composites which are already considered expensive alternatives. A remark must be made that in the test configuration used herein the heat exposure is from above, while in a real fire the GFRP will be oriented such that the fire is from below. As the resin decomposes from solid to liquid to a gas state, this may decrease the resin locally available as fuel since the liquid portions may drop away from the structure by gravity. On the other hand, this may lead to different mechanics of flame spread, so spread and phase changes in various resins should be studied in the future as well.

The distribution of fiber materials in all GFRP bars may not be considered uniform. X-ray technology can typically deduce the distribution. For larger and thicker samples thermal decomposition will take much longer to penetrate within the material and the outer edges of the bar will soften first, changing the amount of distributed load on the outer fibers. If the bulk of the fibers are located away from the core of the bar, this could have consequences in terms of load distribution and carrying ability. This effect merits more study as it may lead to an optimal technique by which to design GFRP structural shapes (bars and SIP formwork for example) depending on the fire exposure.
Emissions of CO and CO_2 over time can be a good indication that other emissions are present in the heating and decomposition processes of the GFRP [4]. From an environmental perspective, emissions released in fires is emerging as an important issue associated with structural fires and one that should be accounted for during PBFD. Uncertainties may also exist regarding the nature or identification of these emissions. Thus, since GFRP materials for SIP formwork are externally exposed in bridge infrastructure, further study should be conducted into possible emissions and their potential impact on the health of nearby populations and responders in the event of fire.

While this is a work in progress, and many hypotheses are presented which require further study, the authors have provided original data which indeed highlight the complexity of behaviour of GFRPs under high temperature exposure. This information can be expanded and used to study state of the art GFRP composite designs in hopes of improving the material so that it can be used in a fire safe and environmentally friendly way.

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