Study of GFRP bars as Internal Reinforcement for Concrete Structures

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ABSTRACT: Corrosion of steel in reinforced concrete structures worldwide has cost a significant amount of resources over the past few decades. Glass fibre reinforcement polymer (GFRP) bars present a cost effective and feasible solution to the problem of steel corrosion. With the certification standard in Canada only recently developed, designers must be aware that the products from individual manufacturers vary greatly even when certified. Based on a comparison of mechanical, material and durability properties, bars from three manufacturers were verified as being quite different but nonetheless suitable for use as primary load carrying tensile reinforcement in concrete structures. Also, from testing of large beams, it was determined that the bond between GFRP and concrete plays a significant role in determining the member behaviour and failure mode, particularly for higher strength bars which require larger anchorage length to develop their tensile capacity.

1 INTRODUCTION

Reinforced and pre-stressed concrete comprise two of the most common structural systems used today around the world, American bridge inventory shows that over 50% of the bridges are made of one of those materials (FHWA 2006). With their wide use, their associated problems have also become a major concern in the engineering community. The corrosion of steel in reinforced concrete structures has cost a significant amount of resources and is the primary cause of structural deficiency in many reinforced concrete structures around the world.

With their extremely high strength to weight ratio and corrosion resistivity, FRP reinforcing rods present an effective alternative to traditional reinforcing steel and a potential solution to the problem of steel corrosion in concrete structures. Fibre Reinforced Polymers (FRPs) of various types and configurations have existed and been used since the end of the Second World War (Tang 1997). Traditional steel reinforcing bars have a standard design and performance regardless of the manufacturer. In contrast, the properties and designs of different FRP rods available in the market place vary considerably. With this background, the certification document to standardize and grade the products for design was prepared by ISIS Canada (ISIS Canada 2006).

The work presented in this paper evaluates the properties of various GFRP bars available today as well as their compliance with the Canadian Certification Document (ISIS 2006). The durability of GFRP bars to environmental exposures including extreme low temperatures is also investigated. The adequacy of GFRP bars as internal reinforcement is studied by evaluating the behaviour of GFRP-reinforced concrete elements.

2 CURRENT CERTIFICATION STANDARDS

"Specifications for Product Certification of FRPs as Internal Reinforcing of Concrete Structures (ISIS 2006)" is the only document for certification of FRP rods in Canada. The tests and guidelines in this document follow closely those of ACI 440.3R-04. The certification standard in Canada grades FRP rods on three categories: strength, stiffness and durability. A variety of minimum requirements is specified in the document for FRP rods made of aramid, carbon and glass. Table 1 lists the tests required for overall ISIS certification for use in Canada (ISIS 2006). GFRP reinforcing rods are graded with a strength designation denoting the ultimate strength, a stiffness rating denoting the modulus of elasticity and a durability designation. In the case of the durability the D1 designation is superior to the D2 and has separate test requirements.

Table 1. Required Tests for ISIS Canada Certification

Strength Properties	Durability Properties
1) Ultimate Tensile Capacity	1) Alkali Resistance
2) Modulus of Elasticity	2) Creep Rupture Stresses
3) Rupture Strain / Ultimate Elongation	3) Cure Ratio (Curing Degree)
4) Bond Strength with Concrete	4) Glass Transition Temperature
	5) Cold Temperature Tensile Properties
	6) Fatigue Strength
	7) Void Content
	8) Water Absorption
	9) Coefficient of Thermal Expansion
	10) Glass Fibre Content

3 RESEARCH PROGRAM AND RESULTS

3.1 Comparison of Mechanical Properties

Part of this research program includes the evaluation of various GFRP bars. Bars from three manufacturers have been compared and assessed based on not only tests conducted at the University of Toronto but those conducted and reported by independent investigators from laboratories around the world. The products evaluated are not identified by their manufacturers' names. Data from all three manufacturers are available for all the required strength tests and is shown in Table 2 along with the ISIS minimum requirement. The numbers compared in the following tables come from the 16mm bar size. As the bar size increases the ultimate strength typically decreases slightly while most other properties remain the same (Kiefer 2007, Volkwein 2007, Pultrall 2007, Hughes Brothers 2007, Abbasi & Hogg 2004) This is reflected by the ISIS certification guidelines having different minimum strength requirements for different sized FRP rods.

Table 2. Comparison of Mechanical Properties for various GFRP manufacturers

Test	ISIS Minimum	Company A	Company B	Company C
Ultimate Strength (MPa)	650	1307	743	751
Modulus of Elasticity (MPa)	35000	64000	44600	48200
Ultimate Elongation (%)	1.2	2.61	1.67	1.56
Bond Strength (MPa)	8	12.21	9.9*	13.7

* denotes one test completed at reference temperature.

A large variation in mechanical properties can be observed in Table 2 from which it can be concluded that these bars cannot be used interchangeably. A significantly revised design will result if bars from one manufacturer are to be replaced with those of another.

3.2 Comparison of Material Properties

The ISIS certification standard outlines ten separate tests under durability. Six of these tests relate to material properties under normal conditions but can affect the long-term performance of the GFRP rods when subjected to various exposures. These material prperties are listed in Table 3 along with minimum ISIS requirements and the values for different bars.

Table 3. Comparison of Material Properties for various GFRP manufacturers

Test	ISIS Standard	Company A	Company B	Company C
Fibre Content (% by Volume)	> 55	74.98	-	60.1
Glass Transition Temperature (^oC) (Test by Dynamic Mechanical Analysis)	> 90 for D2 > 110 for D1	141.6	-	-
Cure Ratio (%)	> 95 for D2 > 98 for D1	93.6	-	-
Void Content (%)	< 1	0	-	-
Transverse Thermal Expansion Coefficient ($x10^{-6}/^oC$)	< 40	22.6	-	29.1
Water Absorption (%)	< 1 for D2 < 0.75 for D1	0.254	-	0.21

Similar to the comparison of mechanical properties it can again be noted that there is a significant variation in the material properties even though for the most part each of manufacturer's products exceed the ISIS requirement. These properties will have some effect on the durability of the products as discussed below.

3.3 Environmental Durability

Table 4 lists three properties of GFRP bars, namely alkali resistance, creep rupture and cold temperature tensile property losses (Dejke 2003, Weber 2007, Nkurunziza et al. 2007). The tests conducted for alkali resistance involved submersion of the FRP reinforcing bars in an alkaline solution of pH ranging from 12.6 to 13.0 at 60^{o}C for 2000 hours (ACI 440.3R). The bars were then tested for their residual direct tensile strength. In the creep rupture tests, the bars were cast into concrete and then subjected to a sustained tensile load of anywhere between 0.2 and 0.8 times their static tensile strength. The failure load and corresponding time to failure are plotted and the millionth hour creep rupture strength is determined from linear regression. For the cold temperature behaviour, the bars were conditioned at -40^{o}C for a minimum of 24 hours and then tested under direct tensile loads at that low temperature (see Section 3.4 for further details).

Table 4. Comparison of Durability Properties for various GFRP manufacturers

Test	ISIS Minimum	Company A	Company B	Company C
Alkali Resistance (% Tensile Capacity after 2000 hours exposure)	70 for D2 80 for D1	87	57.2	91.2
Creep Rupture Strength (% of Tensile Capacity at 1,000,000 hours in Alkali)	35	44.8	-	52.3*
Cold Temperature Tensile Property Loss	No significant loss	Minimal	-	-

*Extrapolation of 10000 hour results

The available data in Table 4 shows that the GFRP bars are quite resistant to the effects of the various simulated environmental exposures. Data was not available for both the creep rupture and cold temperature tests for both companies B and C. It has been reported (Mufti et al. 2007) that the deterioration of GFRP bars for the real-life exposure conditions is far less than that observed in simulated laboratory experiments.

3.4 Cold Temperature Testing Procedure

An experimental program is underway at University of Toronto in which a large number of tensile tests have been conducted on bars at -40^{o}C (Sheikh & Johnson 2007). This temperature represents a severe but possible exposure condition in Canada and is an ISIS (2006) requirement. The tests were conducted in a manner similar to direct tensile tests described in section 3.1, except in these tests the samples were preconditioned to their low temperature and the sample and surrounding environment were constantly kept at -40^{o}C throughout the test procedure. Figure 1 shows the setup of for these tests and a bar specimen after failure.

Figure 1. Setup for Cold Temperature Testing and Failed 16mm Test Specimen

Results from 33 tests on # 16 and #12 bars are summarized in Table 5. It is obvious that there is no significant loss of tensile properties as a result of cold temperature. The ISIS requirement does not specify any limits on the change of tensile properties except that there should be no significant loss. It should be noted that the strength reported for the cold temperature tests provide a lower bound for strength since a majority of the specimens failed by slippage of bars from the couplers. The modulus of elasticity reported in Table 5 is for the initial part of the stress-strain curve up to a stress of about 250 MPa. The 'A' values for the modulus of elasticity and ultimate elongation include the slippage of bars at couplers while the 'B' values were obtained from strain gauge data and its extrapolation. All the strain data for 12 mm bars was obtained from strain gauges.

Table 5- Summary of Properties at Cold Temperature

	Ultimate Strength (MPa)	Modulus of Elasticity (MPa)	Ultimate Elongation (%)
Reference Sample (#12)	1160	56269	2.06
Reference Sample (#16)	1236	63902	2.83
Cold Sample Average (#12)	1120	55893	1.99
Cold Sample Average (#16)	1209	54344 (A) ~60000 (B)	3.04 (A) ~2.2 (B)
Percent of Reference Value (#12)	99.3%	96.5%	96.6%
Percent of Reference Value (#16)	97.84%	85.04% (A) 89.20 % (B)	107.35% (A) 77.00% (B)

3.5 Behaviour of GFRP Reinforced Concrete Elements

To evaluate the behavior of GFRP reinforced concrete sections, a set of large scale beams were constructed and a few of these have been tested. The beams were reinforced with one large GFRP bar of diameter 32mm. Smaller steel bars were also used in the beam to form a reinforcing cage. To prevent failure in shear, adequate shear reinforcement was provided through the use of high strength concrete, transverse steel reinforcement and externally applied GFRP wrap. The beams were tested monotonically until failure. The mode of failure was in concrete bond. The peak stress in the GFRP reinforcing bar at the time of bond failure was calculated to be 998.5 MPa at a crack location. Multiple strain gauges of different sizes were adhered to the GFRP bar in the regions of highest stress. A sketch of beam details is shown in Figure 2.

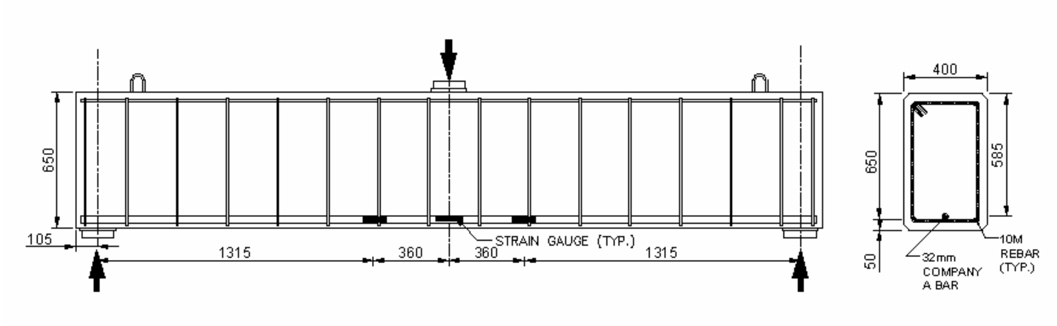

Figure 2 – Beam Details

The calculated bar stress in Figure 3a was determined using typical equilibrium and compatibility conditions. Tension stiffening of the concrete was also considered in this analysis. By fitting a linear function through the calculated stress vs. measured strain response for each of the gauges in Figure 4a, the modulus of elasticity was determined to be approximately 50000 MPa. To compare the results of the experiment with current analytical tools, the beam section was modelled in the Response 2000 analysis software (Collins & Bentz 2000) using bar properties obtained from the experiments. Figure 3b shows a comparison of the analytical and experimental results.

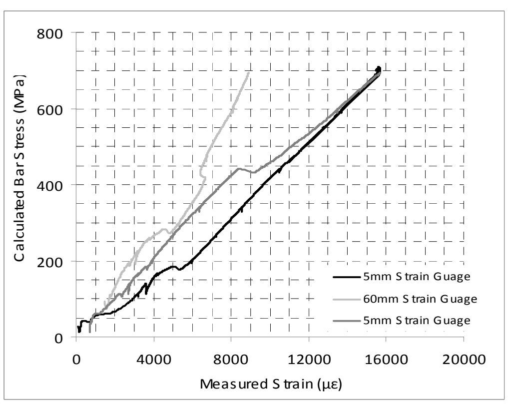

Figure 3a. Stress Strain Response of GFRP bar

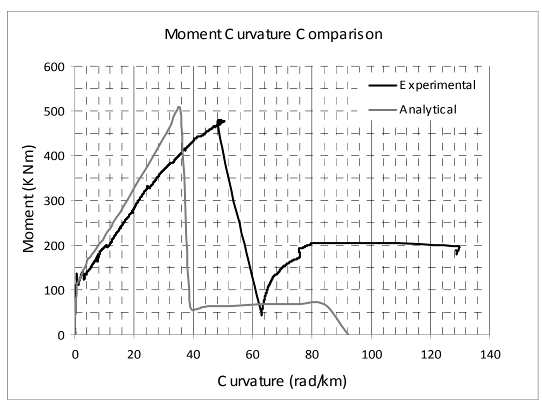

Figure 3b. Comparison of Experimental and Analytical and Results.

The modeling software overestimated the stiffness of the section somewhat. The difference can be primarily attributed to the assumption of perfect bond between the GFRP bar and the concrete, which was not the case in the experiment. The peak bond stress in the member was calculated to be 4.97 MPa. In the pull-out tests on smaller bars, a bond stress of over 12 MPa was reported (see Table 2).

The difference is significant; however, bond behavior in flexural members has been reported to be significantly different from standard pull-out tension tests (Tastani & Pantazopoulou 2002). The beneficial effect of confinement of concrete around the reinforcement is only found in pull-out tests in which the concrete surrounding the bar is mostly in compression. In contrast, reinforcing bars in a flexural member are surrounded by concrete that is either cracked or uncracked but nonetheless in tension. This difference can partly explain the significant drop in bond stress measured in the flexural beam specimen.

4 CONCLUDING REMARKS

The properties of the available GFRP rods vary significantly which makes certification standards necessary. The structural designers must carefully evaluate these differences in properties when selecting the GFRP rods as internal reinforcement for concrete structures. When evaluating the behaviour of GFRP reinforced concrete sections, it was found that the anchorage of reinforcement plays a critical role particularly if the reinforcing bars have high strength. Further tests on large beams and the associated analytical work are needed to fully understand the bond behaviour of GFRP bars in flexure.

Three available GFRP bars were studied for which the limited test data shows that they meet most of the certifications requirements for their use as internal reinforcement in concrete structures. They also display adequate to excellent resistance to environmental exposures that include exposure to cold temperatures and alkalis.

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