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EXPERIMENTAL STUDY ON FLEXURAL PERFORMANCE OF FRC BEAM SPECIMENS FOR BRIDGE BARRIER APPLICATIONS

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Abstract: Fiber-Reinforced Concrete (FRC) are recently used in structural elements in order to provide with more cost-effective design. Although specific details have not yet been provided for FRC bridge barriers in the Canadian Highway Bridge Design Code (CHBDC), a residual strength index with respect of the post-cracking flexural properties of FRC beam specimens is indicated in CHBDC as an initial step for designing FRC bridge barriers. In this study, two flexural-performance standard tests, namely: ASTM C1399 and ASTM C1609, were carried out as mentioned in CHBDC on FRC beam specimens with synthetic macro fiber. The tests provide with the corresponding results for evaluation of the residual strength index required by CHBDC for FRC-reinforced structures. The two tests were conducted on a total of 30 specimens with a size of 200x200x700 mm including three different fiber rates, namely: 0.5%, 1.0% and 1.5%. The results include the average residual strength and modulus of rupture for all specimens for comparison and concluding with an efficient fiber rate for bridge barrier applications.

1 INTRODUCTION

Bridge barriers made of steel reinforced concrete normally suffer from corrosion of the steel by de-icing salt. As a result, constant repair and maintenance is needed to enhance the life cycle of these barrier walls. An alternative approach is to reduce the amount of the steel bars by adding fibers in the concrete mix to produce Fiber-Reinforced Concrete (FRC). Basically, this method of reinforcing the concrete substantially alters the properties of the non-reinforced cement-based matrix which is brittle in nature and possesses little tensile strength compared to the inherent compressive strength. FRC provides provide post-cracking tensile capacity, substantial modulus of elasticity, high tensile strength, and improved fatigue and impact resistance. In addition, it enhances durability by providing low shrinkage, good thermal expansion, better freeze-thaw properties and lower creep strain. Few authors dealt with the environmental properties of the FRC (Brown et al., 2002). Other authors used small beams to obtain mechanical properties of FRC (Giaccio et al., 2008; Ferreira et al., 2008; Qian and Stroeven, 2000).

Although there are only few studies performed on FRC bridge barrier design, there have been many studies conducted on FRC structures and different elements in structures in different aspects. Pervious studies include Finite Element Analysis (FEA) for comparing and optimizing the load transfer and failure mode of precast and cast-in-place bridge barriers (Namy et al., 2015). In another study by Charron et al. (2011), a reduction of traditional steel rebar utilization up to 50% was concluded in FRC bridge parapets with finite element modelling as well as experimental studies. Additionally, some experimental studies on the flexural behavior of FRC beams were conducted on smaller beam sizes to evaluate the FRC rates for bridge barriers (Banthia and Dubey, 2000a and 2000b). However, the authors recommended testing on larger beam sizes as the flexural behavior of FRC beams might depend on the size of the elements.

In this study, the initial step for designing FRC bridge barriers is studied; performing two flexural tests, namely ASTM C1609 and ASTM C1399 on FRC beams with different fiber ratios and larger sizes than ones tested in pervious literature, as per CHBDC requirements. The aforesaid flexural tests provide with the Average Residual Strength (ARS) and the modulus of rupture (R). These two parameters are used for calculating the residual index (R_i) as per defined in the CHBDC for performance evaluation of the FRC beams. The tests are conducted for different fiber rates so an acceptable fiber ratio could be chosen for the FRC bridge barrier design that is safe, economical and practical considering the construction limits.

2 CHBDC REQUIREMENTS FOR FRC BRIDGE ELEMENTS

The Canadian Highway Bridge Design Code (CHBDC) (CSA, 2014) indicates some basic conditions regarding utilizing FRC in various components of bridge structures such as barrier walls. Chapter 16 of CHBDC specifically discusses the concerns of FRC in bridge structures. CHBDC generally allows using fiber reinforcement in types of glass, carbon, aramid, low modulus polymer and steel. However, for FRC, CHBDC criteria allows using carbon, nylon, polypropylene, polyvinyl alcohol, steel and vinylon fibers. Two main parts of chapter 16 of CHBDC discuss conditions of using Fiber-Reinforced Polymer (FRP) and Fiber-Reinforced Concrete (FRC). It is indicated in CHBDC that randomly distributed fiber reinforcement may be used in deck slabs, barrier walls, and surfacing of stressed log bridges for control of developed crack during its early life and may be used for other applications with approval (CSA, 2014). The fiber volume fraction must comply with clause 16.6.2 of CHBDC. For this matter, CHBDC provides with an index of residual strength (R_i) that can be calculated as follows:

[1] $R_i = ARS / R$

Where ARS is the mean value of the average residual strength determined using the ASTM C1399 (ASTM Committee, 2010a) test on at least five fiber-reinforced concrete beam specimens and R is the mean value of the modulus of rupture determined by performing the ASTM C78 (ASTM Committee, 2010b) test on at least five fiber-reinforced concrete specimens.

Although CHBDC indicates ASTM C78 test for calculating R, as this test is not specified for FRC, the more applicable test that provides with the modulus of rupture for FRC is ASTM C1609 (ASTM Committee, 2005). Table 16.3 of CHBDC provides the minimum values of R_i for different conditions of bridge components. Thus, the values calculated from Eq. 1 should meet the requirement mentioned in Table 1. Thus, based on definitions given in Table 1, the fiber volume for FRC barrier must satisfy a minimum of $R_i = 0.25$ when using one mesh of bars.

Table 1: Minimum values of R_i (adopted from CHBDC 2014)

Application	Minimum value of R_i
Barrier wall with one mesh of bars	0.25
Barrier wall with two mesh of bars	0.0*
Deck slab with one crack-control mesh	0.25
Deck slab with two crack-control meshes	0.0*
Surfacing of stressed log bridges	0.30

*Fibers not needed.

3 FRC BEAMS FLEXURAL TESTS

As mentioned in pervious sections, CHBDC requires a minimum residual index (R_i) of 0.25 for an acceptable FRC mix that could be utilized in bridge barriers with only one mesh of rebars. This index is calculated from two ASTM flexural tests (C1399 and C1609). In this section, a brief review of the two tests and the setup that was used for conducting them for this study, is provided.

3.1 ASTM C1399 Test

ASTM C1399 test (ASTM Committee, 2010a) is provided by ASTM Committee for obtaining the average residual-strength of fiber-reinforced concrete using specified beam deflections that are obtained from a beam cracked in a standard manner. The results are shown in a load-deflection curve beyond the point which a significant cracking has occurred. Therefore, the post-cracking strength affected by using fiber can be evaluated. The test is performed on cast or sawed beams of fiber-reinforced concrete. The specimens are cracked using the third-point loading apparatus similar to that specified in other test standards such as ASTM C78 and ASTM C1609 (Figure 1). However, in ASTM C1399 test method, the third-point loading apparatus is modified by a steel plate added at the bottom of the specimen to assist in support of the concrete beam during an initial loading cycle. The use of steel plate helps controlling the rate of deflection when the beam cracks.

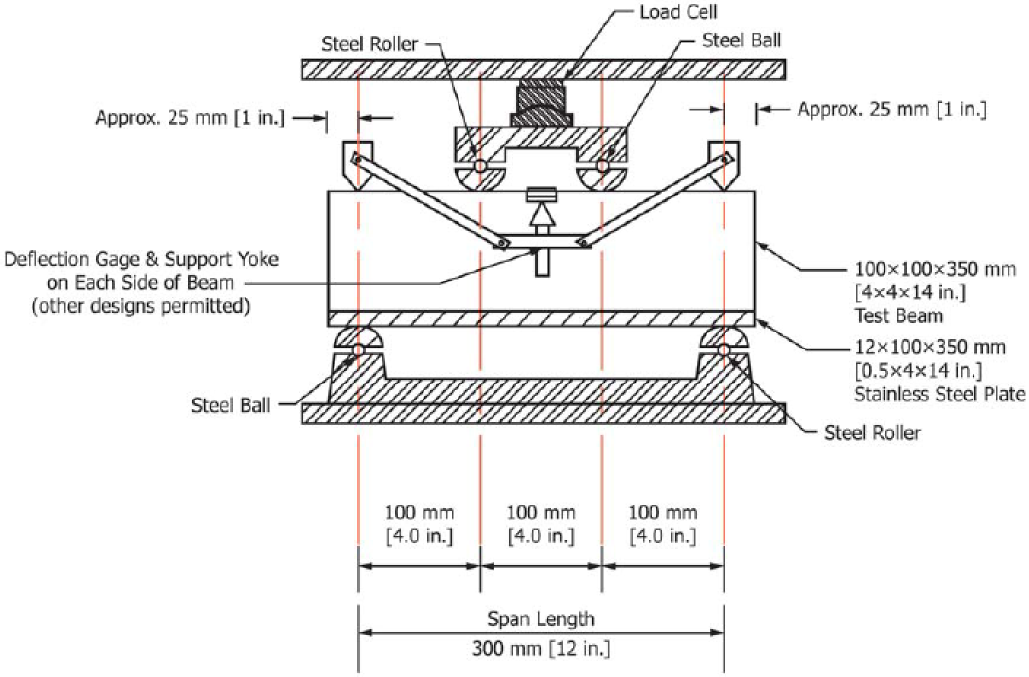

Figure 1: ASTM C1399 schematic apparatus (adopted from ASTM Committee, 2010a)

After the beam has been cracked in specified manner, the steel plate is removed, and the cracked beam is reloaded to obtain data to plot a reloading load-deflection curve. The average residual strength (ARS) for each beam is calculated using the loads determined at the reloading curve deflections of 0.50, 0.75, 1.00 and 1.25 mm (namely: P_A, P_B, P_C, P_D, respectively) as follows:

[2] $$ARS = ((P_A + P_B + P_C + P_D) / 4) \times k$$

Where $k = L / bd^2$ [mm^{-2}], $P_A + P_B + P_C + P_D$ = sum of recorded loads at specified deflections [N], L is the span length [mm], b is the average width of beam [mm] and d is the average depth of beam [mm].

3.2 ASTM C1609 Test

As for the ASTM C1609 test, the third-point loading apparatus is used again, but without the steel plate and using a closed-loop loading rate and system as indicated in the standard test method. A closed-loop loading is defined when the testing machine is operated so the net deflection increases at a constant rate in accordance with guidelines provided in the test method standard (ASTM Committee, 2005). The rate may be changed after reaching the deflection of L/900 (where L is the span length) based on acceptable rates given in the standard. The corresponding parameters are derived from the load-deflection curve obtained from the test, and the values are used in order to calculate the modulus rupture (R) of the beam specimens. Although two preferred sizes of 100x100x350 mm and 150x150x500 mm are recognized in the standard test method, different sizes are mentioned to be permissible. Molded or sawn beam specimens with a square cross-section should be tested in flexure using a third-point loading arrangement similar to that in C1399 or C78 tests but incorporating a closed-loop servo-controlled testing system, and roller supports that are free to rotate.

3.3 Test Setup

The tests were conducted using an MTS loading machine with loading rate control based on deflection. A frame (Figure 2) was used for holding two linear potentiometers (POT) that work similar to Linear Variable Differential Transformers (LVDT) at the sides of the beam and at the center to measure the exact deflection during the tests. For ASTM C1399 test, a steel plate with the same dimensions of the beam and a thickness of 12 mm was used, as per test standard recommendation.

Figure 2: Test setup preparation; frame used for POTs

4 TEST DETAILS AND PROCEDURE

The test matrix included three fiber rates of 0.5%, 1.0% and 1.5% and 5 beams for each of two flexural tests. The fiber rates chosen in this study are similar to the rates considered in previous studies, however, in most of the previous studies lower rates and up to 1.0% was evaluated. As the eventual goal of this study is designing an FRC bridge barrier with reduced amount of steel rebars, rates of fiber in higher range are considered. Also, another objective is investigating the casting and construction process in order to effect of higher rates of fiber on the quality of the mix and any further needs in the process. The fiber used in this study is STRUX 90/40 synthetic macro fiber which is approved by the Ministry of Transportation Ontario (MTO). Benefits of synthetic fibers comparing to steel fibers include being safer in different aspects such as using, handling and finishing, not having pop-ups, corrosion and durability problems that can occur with steel fibers (GCP, 2007). Other properties of STRUX 90/40 macro fiber is provided in Table 2.

Table 2: STRUX 90/40 properties (adopted from GCP, 2007)

Specific gravity	0.92
Absorption	None
Modulus of elasticity	9.5 GPa
Tensile strength	620 MPa
Melting point	160°C
Ignition point	590°C
Alkali, acid and salt resistance	High

A normal concrete with a compressive strength of 35 MPa and a maximum aggregate size of 20 mm diameter was chosen for the mix design with details provided in Table 3. However, since different fiber rates were used for beam specimens, the fiber were added to the concrete before casting of each sets of specimens. As indicated in the table, a superplasticiser (water-reducing admixture) was used in the mix, however, it was added along with the fiber adding process, so the acceptable slump could be achieved for the concrete mix.

Table 3: Concrete mixture properties used for FRC beam specimens

Item	Volume fraction
Cement type GU	390 kg/m^3
Sand	733 kg/m^3
Aggregate: 20 mm	1070 kg/m^3
Water	155 L/m^3
Air	6.5 %
Fiber (STRUX 90/40)	0.5% = 4.7 kg/m^3 1% = 9.4 kg/m^3 1.5% = 14.1 kg/m^3
Master Glenium 7700*	400.0 mL/m^3
Master Air**	230 mL/m^3
w/c ratio	0.397

* BASF – Master Glenium 7700 is a polycarboxylate-based high-range water-reducing admixture;
** Master Air is an air-entraining admixture

The type of bridge barrier considered for this study, is Test Level 5 (TL-5) concrete bridge barrier as per CHBDC definitions. TL-5 is generally proposed for high-volume-traffic highways and speed of 100 km/h for different types of vehicles. Therefore, TL-5 concrete barriers should be the largest barriers among test levels 1 to 5, and the highest impact resistance should be obtained for these barriers. The dimensions of conventional TL-5 concrete barriers (with traditional steel reinforcement and normal concrete) are given in chapter 12 of CHBDC. In table 12.8 of CHBDC, a minimum height of 1.05 m is suggested for TL-5 concrete barriers with traditional reinforcement. Additionally, a proposed TL-5 design using Fiber Polymer Reinforcement (FRP) for TL-5 and one mesh rebar is proposed in chapter 16 of CHBDC with a height of 1.05 m, top thickness of 185 cm and bottom thickness of 435 cm.

Table 4: FRC beam specimen configurations

		Number of beams	
Fiber ratio	Specimen size (mm)	Test Method	
		C1399	C1609
0.5%	200 x 200 x 700	5	5
1%	200 x 200 x 700	5	5
1.5%	200 x 200 x 700	5	5
Total specimens		30	

Therefore, in order to have results more compatible with the TL-5 bridge barrier dimensions, the FRC beam specimen were chosen to have dimensions twice as larger as the typical dimensions studied in previous literature; 200x200x700 mm. For two flexural tests, three fiber rates and five beams for each of the tests, a total of 30 beams were casted for the tests (details in Table 4). The beams were casted and cured as per ASTM standards and tests were carried out after the 28-day period. As recommended in the test standards, since the mix included with fibers, external vibration and rodding was conducted to prevent segregation. The fiber caused a reduction of slump value with the fiber rate increase. Therefore, more water-reducing additives were required. Although, it was seen at the rate of 1.5% fiber the lack of slump and segregation was a challenge in the casting process. Figures 3 and 4 show the test apparatus and setup, and Figure 5 shows the tested beams.

Figure 3: ASTM C1399 test setup (1.5% fiber)

Figure 4: ASTM C1609 test setup (1.0% fiber)

The C1399 test is a two-stage test; the first stage (part A) includes testing the beam with the steel plate and loading until the deflection at the center of the beam reaches 0.2 mm. Based on the ASTM standard, there should be a crack occurred at deflection of 0.2 mm otherwise the test is invalid. Subsequently (part B), the steel plate is removed, and the beam will be reloaded until a minimum deflection of 1.25 mm, so the data could be collected for the calculation of ARS. In this study, for all specimens the crack occurred at the 0.2 mm deflection and the tests were acceptable.

Figure 5: Tested FRC beams (ASTM C1609 - 1.0% fiber)

5 TEST RESULTS

The results include the corresponding diagrams for the two flexural tests (load-deflection diagrams). The ASTM C1399 test provides the ARS value, and ASTM C1609 gives the modulus of rupture (R) for the beam specimens. The results were taken for each of the beams, and all diagrams were considered. As per ASTM standard and CHBDC, the average values of the sets of five beams for each fiber rates must be taken in order to calculate the residual index (R_i). Following, sample diagrams are shown for C1399 and C1609 flexural tests (Figures 6 and 7):

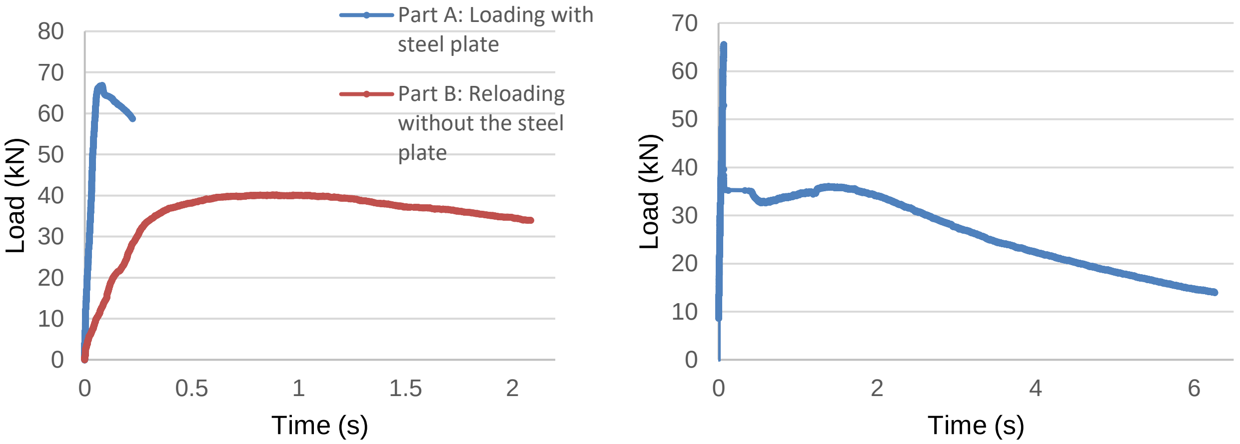

Figure 6: ASTM C1399 results sample (1.0% fiber)

Figure 7: ASTM C1609 results sample (1.0% fiber)

For the sample diagrams shown in Figures 6 and 7, the following data was resulted: ARS = 2.80 MPa (C1399), R = 4.55 MPa, R_i = ARS / R = 0.61. Table 5 shows the data for all tested FRC beams.

Table 5: Results for all FRC beams

	ARS (C1399)	R (C1609)	R_i= ARS/R
1-05	2.20	4.17	0.53
2-05	1.62	2.31	0.70
3-05	1.68	3.60	0.47
4-05	2.41	3.73	0.65
5-05	2.19	4.43	0.49
Average for 0.5% fiber	2.02	3.65	0.57
1-10	2.78	4.32	0.64
2-10	4.57	4.51	1.01
3-10	3.82	4.63	0.83
4-10	2.65	4.79	0.55
5-10	2.80	4.55	0.62
Average for 1.0% fiber	3.32	4.56	0.73
1-15	2.49	4.55	0.55
2-15	3.49	5.26	0.66
3-15	3.16	5.53	0.57
4-15	3.84	5.08	0.76
5-15	4.06	4.52	0.90
Average for 1.5% fiber	3.41	4.99	0.69

The average test results for each sets of beams are provided in Figures 8 and 9, and the evaluated R_i index is shown in Figure 10 and compared the CHBDC requirement (R_i = 0.25). As it can be seen from the results, the residual index (R_i) calculated for all specimens were greater than the CHBDC requirement of 0.25. Therefore, all three fiber rates (0.5%, 1.0% and 1.5%) are acceptable for utilizing in FRC bridge barriers. By comparing the results for the three rates of fiber, an increase of R_i is seen by increasing the fiber rate from 0.5% to 1.0%, however the residual index decreased by increasing the fiber from 1.0% to 1.5%. This can be due to the casting difficulties and a possible segregation of concrete and the fibers.

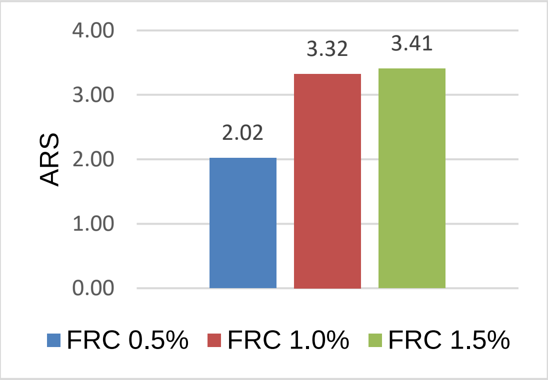

Figure 7: Average results of C1399 test

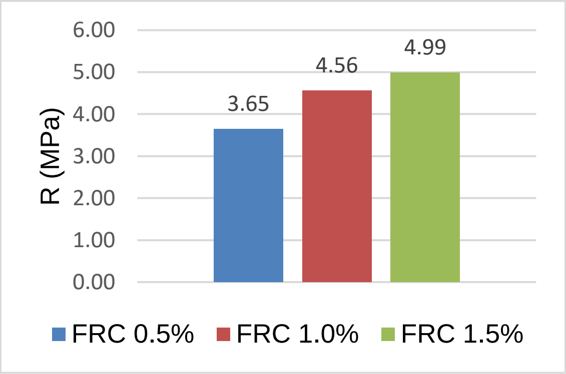

Figure 6: Average results of C1609 test

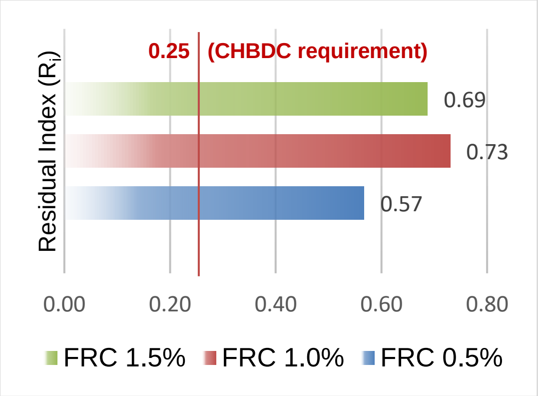

Figure 8: Residual Index (R_i) for all FRC beams

6 CONCLUSIONS

Based on CHBDC, FRC may be used as part of bridge elements upon certain conditions provided in chapter 16. In this chapter it is indicated that a minimum residual index (R_i) of 0.25 is required that the fiber rate of the FRC could be acceptable for bridge barriers with only one mesh of rebars. In this study, 30 FRC beam specimens were casted with three fiber rates of 0.5%, 1.0% and 1.5% for two flexural tests, namely ASTM C1399 and ASTM C1609 for the calculation of the residual index (R_i). The ultimate goal of this study was to find the appropriate fiber rate for TL-5 bridge barriers with removing one mesh of the rebars at the wall, with consideration of the CHBDC requirement as well as practical concerns for casting bridge barriers. The beam dimensions were chosen based on a preliminary TL-5 FRC bridge barrier wall as 200x200x700 mm which is twice the size that were typically studied in previous investigations. A synthetic macro fiber which is already approved by the MTO was utilized for the mix design and beams were casted with normal strength concrete for the tests. Based on the results provided, all FRC beams satisfied the CHBDC requirement and resulted a residual index (R_i) of greater than 0.25. However, results have shown that the residual index increases significantly – almost by 30% – by increasing the fiber rate from 0.5% to 1.0%, while decreases slightly beyond 1.0% (about 6%). Therefore, it was seen that practical issues during casting with higher rate of fiber (in this case, the 1.5% fiber rate) results in the residual index to be decreased. Based on this discussion, a ratio of 1.0% fiber is recommended for a safe, economical and practical design of TL-5 FRC bridge barriers.

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