Behavior of concrete beams reinforced with carbon FRP stirrups

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ABSTRACT: The use of FRP as reinforcement for concrete structures is rapidly increasing. However, limited research has been carried out to investigate the shear behavior of concrete beams reinforced in shear with FRP stirrups. Recently, new CFRP stirrups have been developed and characterized (El-Sayed et al. 2007). However, the behavior of these newly developed FRP stirrups in concrete members needs to be investigated and analyzed prior to be used in construction, particularly for concrete bridge girders. This paper presents the test results of two large-scale New England Bulb Tee (NEBT) beams reinforced with 9.5-mm diameter carbon FRP stirrups spaced at 300 mm (SC-9.5-2) and 200 mm (SC-9.5-3). The test results showed the adequate performance of the used carbon FRP stirrups. However, compared to the test results, the provisions of the Canadian Highway Bridge Design Code, CHBDC (CSA 2006) provided a conservative shear strength prediction for the tested beams.

1 INTRODUCTION

In a previous work conducted by the authors, new carbon FRP stirrups have been developed and characterized through a collaboration project between the University of Sherbrooke, Ministry of Transport of Québec (MTQ) and a Canadian FRP manufacturer (El-Sayed et al. 2007). However, the behavior of these newly developed FRP stirrups in concrete members needs to be investigated and analyzed prior to be used in construction, particularly for concrete bridge girders. Moreover, the use of FRP as shear reinforcement (stirrups) for concrete members has not been sufficiently explored to provide a rational model or satisfactory guidelines to predict the shear behavior and strength of concrete members reinforced with FRP stirrups.

This paper presents an experimental study conducted to investigate the shear performance of carbon FRP stirrups employed in large-scale New England Bulb Tee beams (NEBT) simulating the actual beams that are currently in use MTQ. The design details of these test beams are explained elsewhere (Ahmed et al. 2007). The test results of the beam specimens are presented and discussed herein.

2 TEST SPECIMENS

The beams are 7.0 m long with a simply supported clear span of 6.0 m with an overhang of 0.5 m on each side to provide adequate development length and prevent bond slip failure of the flexural reinforcing bars. The beams have a T-shaped cross section (NEBT) measuring a total height of 700 mm, web width of 180 mm, flange width of 750 mm, and flange thickness of 85 mm. The test specimens were reinforced in flexure with nine 7-wire high tensile steel strands of 15.4-mm diameter (Area = 140 mm^2). The high strength steel strands were selected to provide a flexural strength greater than the shear capacity for the test beams. However, the shear reinforcement was CFRP stirrup spaced at 300 mm (d/2) for beam SC-9.5-2 and 200 mm (d/3) for beam SC-9.5-3. Figure 1 shows the details of test beams.

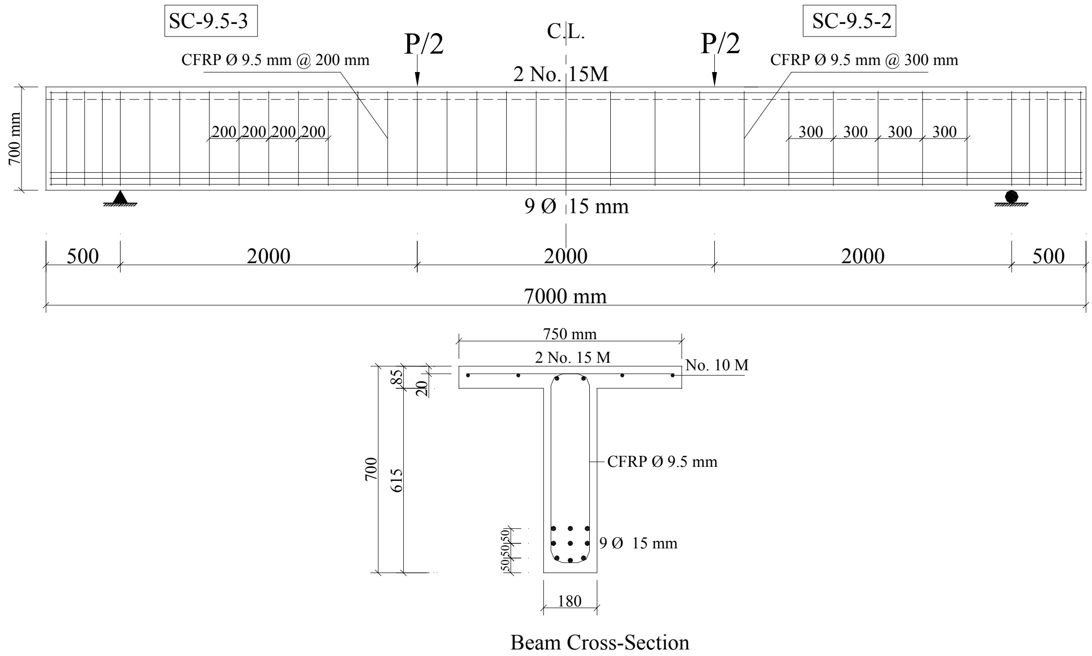


Figure 1. Geometry and reinforcement details of test beams.

The test specimens were designed according to the provisions of the CHBDC CSA (2006). The shear strength was determined as follows:

$$V_r = V_c + V_{FRP} \tag{1}$$

The concrete shear contribution:

$$V_c = 2.5\,\beta\,\phi_c\,f_{cr}\,b_v\,d_v \tag{2}$$

The FRP stirrups contribution:

$$V_{FRP} = \frac{\phi_{frp}\ A_{fv}\ \sigma_v\ d_v\ \cot\theta}{s} \tag{3}$$

such that:

$$\beta = \frac{0.4}{\left(1+1500\,\varepsilon_x\right)} \cdot \frac{1300}{\left(1000+S_{ze}\right)} \tag{4}$$

$$\theta = \left(29+7000\,\varepsilon_x\right)\left(0.88+S_{ze}/2500\right) \tag{5}$$

$$\varepsilon_x = \frac{\left(M_f/d_v\right)+V_f-V_p+0.5N_f-A_p f_{po}}{2\left(E_s A_s + E_p A_p\right)} \le 0.003 \tag{6}$$

where σ_v is the smaller of the following values:

$$\sigma_v = \left(0.05 r_b/d_b + 0.3\right) F_{FRPbend}/1.5 \tag{7.a}$$

$$\sigma_v = E_{vFRP}\varepsilon_v \tag{7.b}$$

$$\varepsilon_v = 0.0001\left[f_c'\,\frac{\rho_s\,E_{FRP}}{\rho_v\,E_{vFRP}}\right]^{0.5}\left[1+2\left[\frac{\sigma_N}{f_c'}\right]\right] \le 0.0025 \tag{7.c}$$

According to the proposed dimensions, reinforcement and actual concrete strengths of the test specimens, the shear design capacity (CSA 2006) was 189 kN for the two test specimens (SC-9.5-2 and SC-9.5-3). It is worth mentioning that the predicted shear strengths are governed by the stress limits (Eq. 7).

3 MATERIAL PROPERTIES

The test specimens was cast in the laboratory at the University of Sherbrooke, using ready-mixed normal weight concrete (Type V, MTQ) with a 28-day targeted compressive strength of 35 MPa. The obtained compressive strengths for the SC-9.5-2 and SC-9.5-3 beams were 42 and 35 MPa respectively. On the other hand, the tensile strengths obtained from the splitting test of concrete cylinders were 3.03 and 2.9 MPa respectively.

Pre-fabricated CFRP stirrups No 10 (9.5-mm diameter) were used as shear reinforcement. The CFRP bars were made of continuous longitudinal carbon fibers impregnated in a thermosetting vinyl ester resin using infusion process. The CFRP stirrups had a sand-coated surface to enhance bond performance between bars and surrounding concrete. The bend radius (r_b) was 38.1 mm which represent 4 times the bar diameter (d_b). Figure 2 shows the dimensions of the CFRP stirrups. The average tensile strength for the straight part of the stirrups was 1538 MPa, while the capacity of the CFRP stirrup at the bend was about 789 MPa. The obtained modulus of elasticity of the CFRP bars was 130 GPa. All the CFRP reinforcement used in this study are manufactured and developed by Pultrall Inc., Tetford Mines, Quebec, Canada (2005).

Deformed steel bars No. 15M (15.9-mm diameter) and 10M (11.3-mm diameter) were used for top of the beam web and slab reinforcement, respectively. The yield stress and modulus of elasticity of these deformed steel bars were 450 MPa and 200 GPa. However, the 7-wire steel strands, used as bottom flexural reinforcement, had a tensile strength and modulus of elasticity of 1860 MPa and 200 GPa, respectively.

4 TEST SETUP AND PROCEDURE

The beams are tested in four-point bending over a simply supported clear span of 6000 mm with an overhang extra part of 500 mm. To prevent the local failure under the loading plates, two 10-mm thick rubber sheets are used under the loading plates and over the supports as well. The load is monotonically applied using two actuators of 1000 kN capacity with a load controlled rate of 5 kN/min. The two actuators are connected to the same pump and they are adjusted to work simultaneously. The two actuators are attached to a very rigid beam that tied to two steel frames fixed to the rigid floor of the laboratory. To prevent the in-plane translation and out-of-plane movement of the two actuators they are connected together using a rigid beam keeping a constant distance between the two actuators and each of them is attached to one frame using two struts. The complete test set-up is shown in Figure 3.

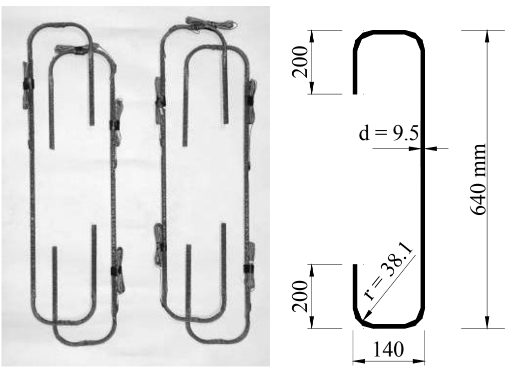


Figure 2. Details of the used carbon FRP stirrups

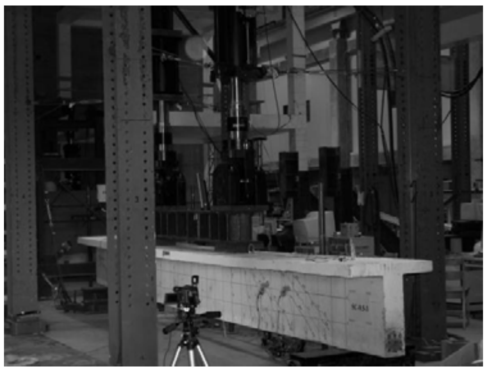
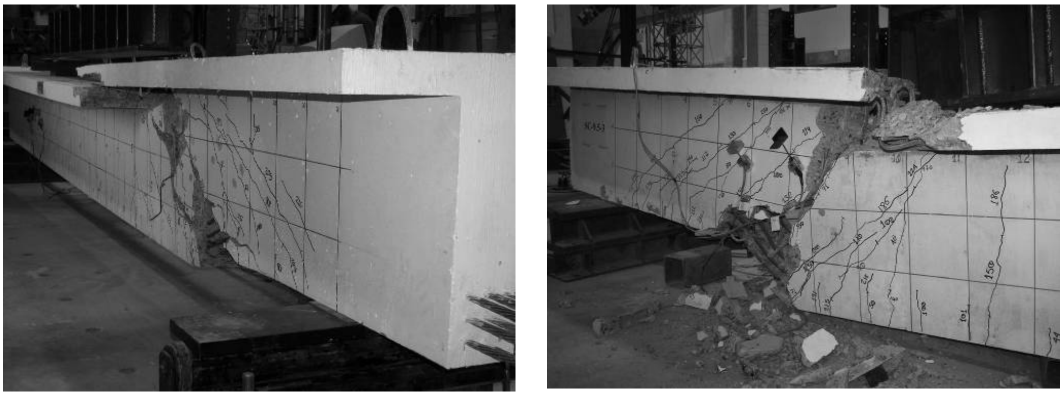


Figure 3. Details of loading setup.

5 TEST RESULTS

5.1 *Shear capacity and mode of failure*

Despite the difference in the load level at which shear failure of beams SC-9.5-2 and SC-9.5-3 took place, a similar failure mechanism was observed in both beams. Diagonal tension failure occurred suddenly for the two beams due to rupture of CFRP stirrups. The failure initiated by the rupture of the CFRP stirrups at the bend part. Consequently, the remaining components of the shear resisting mechanism could not resist the applied shear force and the beam failed in shear. The test specimens failed at a corresponding applied shear of 376 and 440 kN for SC-9.5-2 and SC-9.5-3, respectively. Figure 4 shows the failure of the test specimens.



(a) (b)

Figure 4. Shear failure of test specimens: a) SC-9.5-2 (d/2); b) SC-9.5-3 (d/3).

5.2 Shear crack width and stirrup strain

A limiting crack width is specified in most of the design codes for conventionally reinforced concrete structures to protect the reinforcing steel bars and stirrups from corrosion, with its related deteriorations, as well as aesthetic consideration. Since FRP has a non-corrodible nature, the serviceability limits for crack width of FRP-reinforced concrete elements may be directly related to aesthetic considerations. The CSA (2002; 2006) specifies a limiting crack width of 0.5 mm for exterior exposure (or aggressive environments) and 0.7 mm for interior exposure (or other members). The ACI (2006) recommends that the CSA (2002) limits shall be used in most cases.

The shear spans were visually monitored till the first shear crack appeared. Then after, the initial shear crack width was measured using hand-microscope (50X) and high accuracy LVDTs (±0.001) were attached to continuously record the shear crack width till the beam failure. Figure 5 shows the applied shear force-shear crack width relationship whereas Figure 6 shows the relationship between the applied shear force and the average stirrup strain measured at the mid-height of the straight portion.

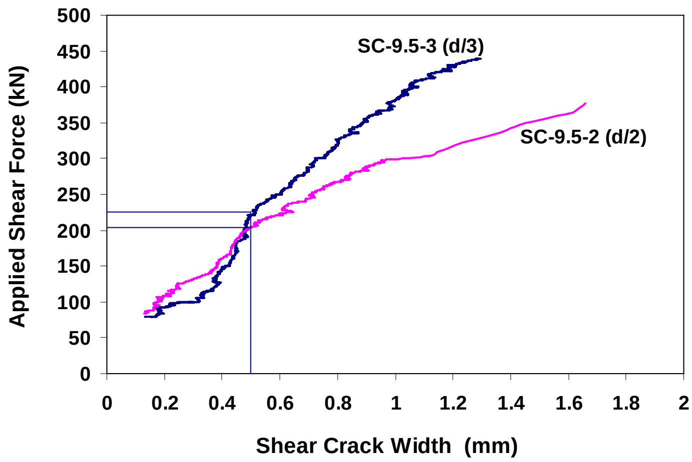


Figure 5. Applied shear force-shear crack width relationship.

Corresponding to an average strain value of 2500 microstrain in the CFRP stirrup, which is the maximum allowable stirrup strain specified by Clause 16.8.6 of the CHBDC (CSA 2006), the applied shear force was 201 kN and 185 kN for the two beams SC-9.5-2 and SC-9.5-3, respectively. Furthermore, the applied shear force corresponds to that strain limit was almost equal or greater than the predicted ultimate capacity using the CSA-(2006) provisions (189 kN for both beams (SC-9.5-2 and SC-9.5-3)).

At failure, the maximum strain recorded on the straight portion of the stirrups was about 7700 microstrain. However, the estimated values from Equation (7.c) were 1245 and 1524 microstrain for beam SC-9.5-2 and SC-9.5-3, respectively. Besides, the failure strain at the bent portion of the CFRP stirrups was also greater than the calculated one based on Equation (7.a). Thus, both of the two equations that limiting the ultimate strain in the FRP stirrups are very conservative.

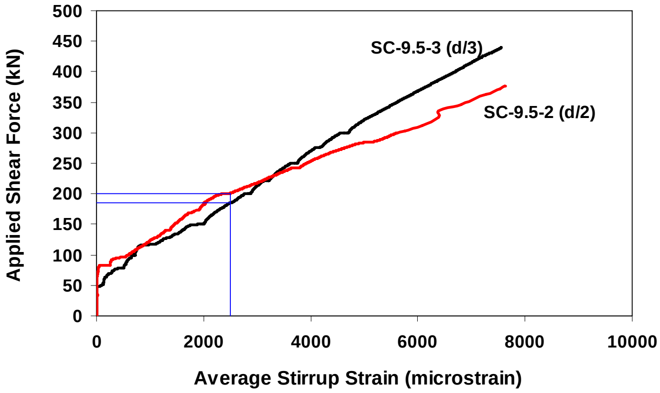


Figure 6. Applied shear force-average stirrup strain relationship.

On the other hand, the ACI (2006) uses a 4000 microstrain limit at ultimate. This limit is justified as it represents the strain level at which the degradation of aggregate interlock and corresponding concrete shear starts to sharply decrease (Priestley et al. 1996). The effective stirrup stress calculated using the ACI (2006) equation at failure with respect to the ultimate strength of the stirrups was 76% and 68% for the beams SC-9.5-2 and SC-9.5-3 respectively.

6 SUMMARY AND CONCLUSIONS

Two large-scale, New England Bulb Tee beams (NEBT), reinforced longitudinally with 9-seven-wire steel stands and transversally with CFRP stirrups spaced at one-half and one-third the beam effective depth were constructed and tested to failure. The beams were 7.0 m long with a T-shaped cross section measuring a total height of 700 mm, web width of 180 mm, flange width of 750 mm, and flange thickness of 85 mm. Based on the test results, the following conclusions regarding the tested CFRP stirrups can be drawn:

1. The used carbon FRP stirrups completely fulfill the requirements of the Canadian Highway Bridge Design Code (CSA 2006).
2. Limiting the stirrup strain at ultimate to 2500 microstrain at ultimate as specified by the CSA (2006) may lead to a very conservative prediction of the shear strength of RC elements reinforced with CFRP stirrups. However, this limit may be relaxed to 4000 microstrain as specified by the ACI (2006).

7 ACKNOWLEDGMENTS

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9 NOTATIONS

A_p	= the area of steel tendons in the tension zone (mm^2)
A_s	= the area of cross-section of steel or FRP reinforcing bars (mm^2)
b_v	= the effective width of web within depth d_v (mm)
d_b	= the bar diameter (mm)
d_v	= the effective shear depth for longitudinal reinforcement (mm)
E_{FRP}	= the modulus of elasticity of FRP bars
E_s	= the modulus of elasticity of steel (MPa)
E_{vFRP}	= the modulus of elasticity of FRP stirrups (MPa)
f_c'	= the specified compressive strength of concrete (MPa)
f_{cr}	= the cracking strength of the concrete (MPa)
$f_{FRPbend}$	= the specified tensile strength of the straight portion of he FRP bent stirrup (MPa)
f_{po}	= the stress in tendons when the stress in the surrounding concrete is zero (MPa)
M_f	= the factored moment at a section (N.mm)
N_f	= the factored axial load normal to the cross-section occurring simultaneously with V_f, including the effects of tension due to creep and shrinkage (N)
r_b	= the radius of curvature of the bend of an FRP stirrup (mm)
s	= the spacing of shear reinforcement (mm)
s_z	= the crack spacing parameter
s_{ze}	= the equivalent crack spacing parameter, shall not be taken less than 0.85s_z
V_c	= the factored shear resistance provided by tensile forces in concrete (N)
V_f	= the factored shear force at a section (N)
V_{FRP}	= the factored shear resistance provided by the FRP shear reinforcement (N)
V_p	= the component of in the direction of the applied shear of all the effective prestressing forces crossing the critical section factored by □ (N)
V_r	= the factored shear resistance (N)
ε_v	= the strain in an FRP stirrup
ε_x	= the longitudinal strain at mid-height of the cross section
θ	= the angle of inclination of the principal diagonal compressive stress (degrees)
ρ_s	= the ratio of the cross-sectional area of the longitudinal reinforcement to the effective cross-section are of the beam
σ_N	= the stress in concrete due to axial loads (MPa)
σ_v	= the vertical stress (MPa)