Flexural behaviour of concrete beams strengthened with near surface mounted FRP bars

S.M. Soliman[1], E. El-Salakawy[2] & B. Benmokrane[3]
[1,3] *Department of Civil Engineering, University of Sherbrooke, Sherbrooke, QC, Canada*
[2] *Department of Civil Engineering, University of Manitoba, Winnipeg, MB, Canada*

ABSTRACT: This research is designed to investigate the behaviour of concrete beams strengthened in flexure with NSM FRP bars. A total of nine full-scale concrete beams (3100 mm-long × 200 mm-wide × 300 mm-deep) were constructed and tested till failure. Different parameters including type of FRP bars, bar diameter, and bonded length were investigated in this research. Test results showed that the use of NSM FRP bars is feasible and effective for strengthening concrete structures. This technique was successful to increase the flexural strength of concrete beams. Using NSM glass or carbon FRP bars increased the carrying capacity of the tested beams, in a similar way, by approximately 100%. However, beams strengthened with GFRP bars showed more deflection at failure than those strengthened with CFRP bars.

1 INTRODUCTION

Near surface mounted (NSM) fiber reinforced polymer (FRP) reinforcement is one of the latest and most promising strengthening techniques for reinforced concrete (RC) structures. In the NSM FRP technique, grooves are first cut into the concrete cover of a RC beam or slab, then FRP bars/strips are inserted and bonded with an appropriate binding agent; typically epoxy paste or cement grout. The use of NSM reinforcement for RC structures is not a new invention. The first application was used to strengthen a bridge deck slab in Lapland, Finland in 1940s. Since the negative moment zone of the deck slabs needed strengthening, steel bars were placed in slots in the top concrete cover using cement grout (Asplund 1949). Nowadays, FRP bars/strips can be used instead of steel and epoxy paste can replace cement mortar. The use of the non-corrodible FRP reinforcement is very advantageous since in the NSM technique the reinforcing bars can be placed very close to the surface, (De Lorenzis et al. 2002; Cruz and Barros 2004; Nanni et al. 2004; Teng et al. 2006; Soliman et al. 2007 and 2008). The main objectives of this research program are: (1) to develop/utilize a NSM system composed of carbon FRP V-ROD bars manufactured by Pultrall Inc. (2005) and adhesives manufactured by Hilti Inc. (2005); (2) to study the flexural behaviour of concrete beams strengthened with NSM FRP bars, in terms of cracking, deflection, carrying capacity, and mode of failure, having different bonded lengths; and (3) to investigate the feasibility of using glass FRP composite bars in the NSM technique.

2 EXPERIMENTAL WORK

2.1 *Material properties*

All tested specimens were constructed using a ready-mixed concrete with a targeted 28-day concrete compressive strength of 35 MPa. The actual concrete compressive and tensile strengths were determined based on standard cylinder tests (three cylinder specimens, 150 × 300 mm, for each concrete batch). The cylinders were tested at the same time of testing the specimen. The obtained concrete compressive strength ranged between 38 and 44 MPa.with a standard deviation of 2.85 MPa. The average concrete tensile strength ranged between 2.9 and 3.6 MPa with a standard deviation of 0.29 MPa.

Two types of sand-coated FRP bars were used in this study, carbon and glass (Pultrall Inc. 2005). Two diameters were used for carbon (9.5 and 12.7 mm), while only one diameter (12.7 mm) was used for glass. All FRP bars were tested to obtain the tensile strength and modulus of elasticity according to the ACI 440.3R-04 guideline (ACI Committee 440 2004). Deformed steel bars No.10M (11.3 mm-diameter) were used in reinforcing the concrete beams. The properties of the steel and FRP reinforcing bars used in this study are listed in Table 1.

An epoxy adhesive, type HIT RE 500 produced by Hilti Inc. (2005) was used in this study. The HIT RE 500 is a high strength two-part epoxy based adhesive. This type of adhesive, which can be applied on wet or dry surfaces, is specially designed for fastening into solid base materials in a wide range of material temperatures (49°C down to -5°C). The tensile strength and modulus of elasticity of the HIT RE 500 adhesive are 43.5 and 1493 MPa, respectively.

Table 1. Mechanical properties of the reinforcing bars

Bar type	Bar diameter, mm	Bar area, mm^2	Modulus of elasticity, GPa	Tensile strength, MPa	Ultimate strain %
CFRP	9.5	71	122±2.4	1536±18	1.22±0.07
	12.7	127	134±9	986±50	0.74±0.05
GFRP	12.7	127	42±1	749±27	1.8±0.04
Steel (10M)	11.3	100	200	f_y = 454 f_u = 571	0.23

2.2 *Strengthening procedures*

Following the 28-day curing period, the test beams were placed upside down to cut the grooves. A special concrete saw, with a diamond blade, was used. The groove was made by making two cuts then chopping the concrete in between as shown in Fig. 1. The groove was square in shape with a side length equals twice the diameter of the FRP bar.

A steel brush was used to clean the groove and pressurized air was used to ensure that the groove is completely clean. The epoxy was injected into the groove to cover 2/3 of the groove depth. The bar was gently inserted into the groove over a plastic support outside the bonded length to maintain the thickness of the epoxy and to center the bar in the middle of the groove. The bar was gently pressed to displace the bonding agent. Extra adhesive was added to fill the groove. The excess epoxy was then removed as shown in Fig. 2. Quality control was achieved by continuous inspection and measurements during all the installation process.

Figure 1. Cutting the groove

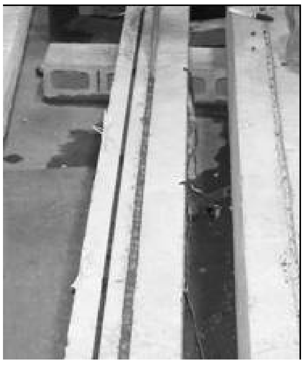

Figure 2. NSM FRP bar installation

2.3 *Test specimens, setup and procedure*

A total of nine RC beams strengthened with NSM FRP bars were tested to failure. The dimensions of the beams were 3010 mm-long, 200 mm-wide and 300 mm-deep. Two No. 10M steel bars were used in the bottom and top of the beams as tension and compression reinforcement, respectively. Two-legged, 8-mm diameter steel stirrups spaced at 100 mm over the whole length of the beam were used to avoid any shear failure. Figure 3 shows the dimension and the reinforcement details for the tested beams. The beams were tested in four-point bending over a simply supported clear span of 2600 mm. A 500 kN closed-loop MTS actuator was used to apply the load as shown in Fig. 4. The rate of loading was 0.02 mm/sec up to failure.

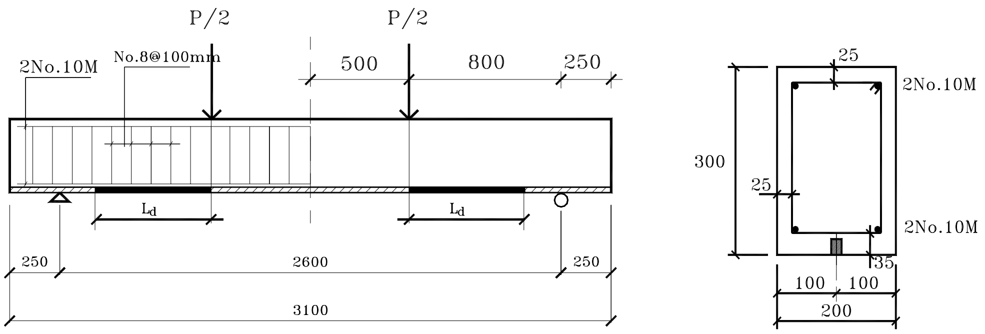

Figure 3. Dimension and reinforcement details of the test beams

One beam was tested as a control specimen, B0, to obtain the capacity of the unstrengthened beams. The test beams are divided into three series. Series 1 consists of 4 beams; namely B1 to B4. Each beam is strengthened with one 9.5 mm-diameter CFRP bar inside a square groove (19 mm). The test parameter in this series is the bonded length; 12d, 24d, 48d and 60d for B1, B2, B3, and B4, respectively, where d is the bar diameter. Series 2 consists of 2 beams (B5 and B6) strengthened with 12.7 mm-diameter CFRP bar inside a square groove (25.4 mm) utilizing two different bonded lengths (24d and 48d) for the two beams. Series 3 consists of 2 beams (B7 and B8) corresponding to beams B5 and B6 except they are strengthened with 12.7 mm-diameter GFRP bars. The beams in series 3 were tested to investigate the feasibility of using GFRP bar in the NSM strengthening. Table 2 summarizes the test specimens.

Table 2. Description of test specimens for the flexural strengthening

Specimen code	Type of FRP	Diameter of FRP	Groove width	Bonded length
B0	Control			
B1	Carbon	9.5 mm	2d (19 mm)	12d
B2				24d
B3				48d
B4				60d
B5	Carbon	12.7 mm	2d (25.4 mm)	24d
B6				48d
B7	Glass	12.7 mm	2d (25.4 mm)	24d
B8				48d

Note: d is the diameter of the NSM FRP bar

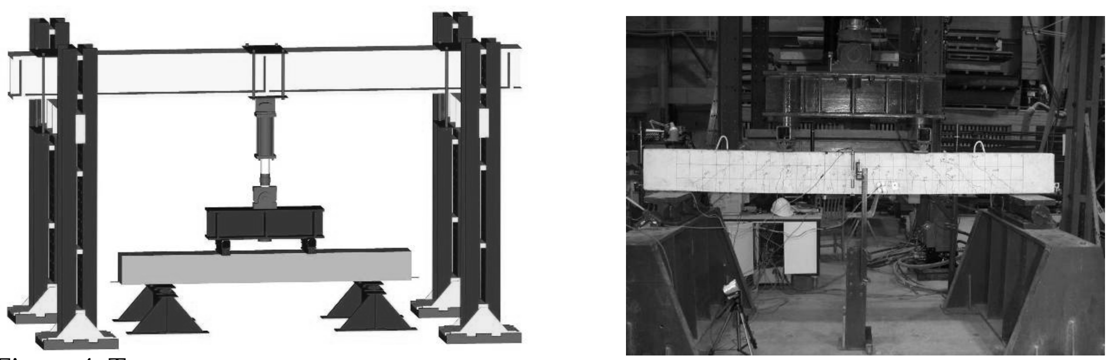

Figure 4. Test setup

3 TEST RESULTS AND DISCUSION

3.1 *Load-deflection behaviour*

Figure 5 shows the load-deflection curves for beams of series 1. This figure shows that the strength and the stiffness of the strengthened beams were significantly improved due to the addition of the CFRP reinforcement.

Before cracking, all the strengthened beams exhibited similar behaviour to the unstrengthened beam. This is expected since before cracking the behaviour depends on the concrete section. After cracking and up to yielding of the internal steel reinforcement, all beams, including the control, have similar behaviour but showing lower stiffness than that before cracking. Following steel yielding and up to failure, the flexural stiffness and strength of the strengthened beams were significantly increased.

The control beam, B0, failed due to steel yielding followed by crushing of concrete at a load of 55.0 kN. Beam B1 with the shortest bonded length (12d) failed at load of 66.9 kN showing an increase of 22% in the ultimate carrying capacity compared to B0. Beams B2, B3 and B4 failed at loads of 72.6, 93.9 and 96.4 kN showing an increase in the ultimate carrying capacity of 32, 71 and 75%, respectively.

It can be observed that as the bonded length increased the ultimate load is increased. However, increasing the bonded length from 24d to 48d increased the carrying capacity by approximately 30%. While increasing the bonded length from 48d to 60d gave only a 2.6% increase in the ultimate capacity. This means that increasing the bonded length increases the ultimate carrying capacity up to a certain limit beyond which the increase in the bonded length will not result in any increase in the capacity.

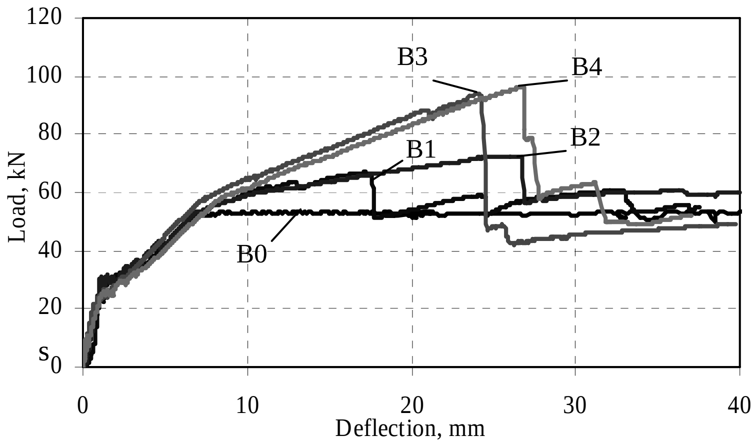

Figure 5. Load-deflection behaviour for beams strengthened with 9.5 mm-diameter CFRP bars

For the two beams of series 2, B5 and B6 with bonded lengths of 24 and 48d, the measured loads at failure were 66.5 and 108.5 kN, respectively. These loads represent an increase in the carrying capacity 21 and 97 %, respectively. On the other hand, the corresponding beams, B7 and B8 strengthened with GFRP bars, failed at loads of 71 and 112 kN showing an increase in the carrying capacity of 29 and 104%, respectively. Figure 6 shows the load-deflection curves for beams B5 to B8. It can be observed from this figure that compared to B5 and B6, beams B7 and B8, utilizing glass FRP bars, carried slightly higher loads to failure but showed lower stiffness for loads above the steel yielding load level. This was due to the lower modulus of elasticity of GFRP bars. However, this can be considered advantageous since the GFRP beams had similar carrying capacity but exhibited much more deflection (50 mm) at failure compared to their CFRP counterparts (19 mm).

The maximum measured CFRP strains at failure ranged from 20 % to 75% of the rupture strain depending on the bonded length used for strengthening. Hassan and Rizkalla (2004) reported that the maximum measured CFRP strain at failure was about 45% for the maximum bonded length used.

All the strengthened beams failed by FRP debonding in the form of concrete cover splitting at the level of steel reinforcement as shown in Fig.7. The debonding stared at the cut-off point of the FRP bar. This mode of failure was observed by other researchers (Teng et al. 2006). Table 3 summarizes the results for the tested beams.

Table 3. Test results

Specimens code	L_b	P_y, kN	Δ_y, mm	P_y %	P_u, kN	Δ_u, mm	P_u %	ε_f	$\varepsilon_f/\varepsilon_{fu}$ %	Ductility Index	Failure mode
B0	—	51.68	6.77	—	54.95	75.89	—	—	—	11.21	C
B1	12d	57.15	8.43	10.6	66.89	17.20	21.7	2424	19.9	2.04	Cs
B2	24d	53.63	7.08	3.8	72.64	25.38	32.2	5059	41.5	3.58	Cs
B3	48d	57.65	7.38	11.6	93.87	23.97	70.8	8583	70.4	3.25	Cs
B4	60d	59.47	9.06	15.1	96.37	26.80	75.4	8595	70.5	2.96	Cs
B5	24d	58.66	8.06	13.5	66.51	19.71	21.0	2026	27.4	2.45	Cs
B6	48d	76.29	9.80	46.2	108.53	18.97	97.5	5650	76.4	1.94	Cs
B7	24d	53.61	9.08	5.77	70.98	25.54	29.2	7515	41.8	2.81	Cs
B8	48d	59	9.19	13.5	112.04	49.36	103.9	15333	85.2	5.37	Cs

C refers to steel yielding followed by concrete crushing

Cs refers to debonding by concrete cover splitting

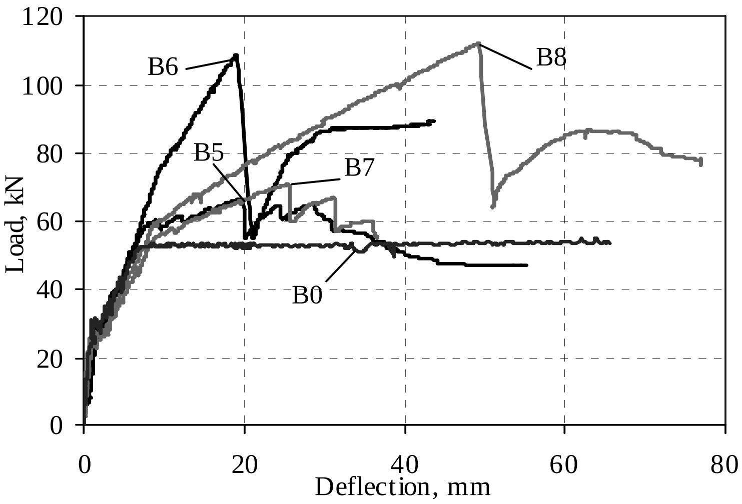

Figure 6. Load-deflection behaviour for beams strengthened with 12.7 mm-diameter CFRP &GFRP bars

Figure 7. Concrete cover splitting failure

4 CONCLUSIONS

Based on the findings of this investigation, the following conclusions can be drawn.

- The proposed NSM FRP/adhesive system is effective to increase both stiffness and flexural capacity of concrete beams. Using NSM FRP bars, with bonded length not less than 48 times the bar diameter, increased the carrying capacity of the tested beams by approximately 100% over the unstrengthened one.
- Increasing the bonded length increases the ultimate carrying capacity up to a certain limit beyond which the increase in the bonded length will not result in any increase in the capacity. It seems that this limit is in the range of 24 to 48 times the bar diameter.
- Compared to carbon FRP bars, glass FRP bars as strengthening reinforcement provided similar increase in the beam carrying capacity. However, due to the low modulus of elasticity of the GFRP bars, beams strengthened with GFRP bars showed more deflection at failure (more than 2.5 times), and consequently higher deformability factors, than those utilizing CFRP bars. This result makes it very attractive to deeply investigate the use of glass FRP bars in this technique.
- The maximum measured FRP strain at failure was about 75 and 85% of the rupture strain of the FRP material for beams strengthened with CFRP and GFRP bars, respectively.
- The mode of failure for the strengthened beams was debonding in the form of concrete cover splitting at the level of the steel reinforcement.

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