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EFFECTIVENESS OF NEAR SURFACE MOUNTED FRP REINFORCEMENT FOR FLEXURAL STRENGTHENING OF REINFORCED CONCRETE BEAMS

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ABSTRACT: This paper presents test results of seven reinforced concrete T-beams strengthened in flexure with different strengthening systems using FRP rebars and strips as near-surface mounted (NSM) reinforcement in addition to FRP strips as externally bonded reinforcement. The FRP reinforcements used in this investigation included carbon-fiber-reinforced-polymer (CFRP) rebars and strips, and glass fiber-reinforced-polymer (GFRP) thermoplastic strips. The behavior and effectiveness of the materials used for the various NSM and externally bonded FRP strengthening systems are compared. The structural performance and modes of failure of the tested beams are presented and discussed in this paper. Test results indicated that using NSM-FRP rebars and strips is practical and significantly improved the stiffness and increased the flexural capacity of reinforced concrete beams. Limitation of using NSM-FRP rebars and strips is controlled by serviceability requirements in terms of overall deflections and crack widths of the member rather than delamination, observed by many researchers, of externally bonded FRP reinforcement. Strengthening of reinforced concrete beams using NSM FRP strips provided the highest strength capacity than externally bonded FRP strips using the same material with same axial stiffness.

1. INTRODUCTION

Fibre-Reinforced-Polymer (FRP) reinforcements have been recently used extensively as an alternative reinforcement material to steel for new construction as well as for strengthening and repair of existing concrete structures. Externally bonded FRP sheets and strips are currently the most commonly used techniques for flexural and shear strengthening of concrete beams and slabs. Several researchers reported that the failure of members strengthened with externally bonded FRP sheets and strips could be brittle due to debonding and/or peeling of the FRP reinforcements especially in the zones of high flexural and shear stresses [1]. Externally bonded FRP reinforcements could be highly susceptible to damage from collision, fire and temperature, ultraviolet rays, and moisture absorption (ACI 440R-96). In some cases, insufficient protection may reduce the service life of the structure. To minimize these problems, and to improve utilization of the FRP materials, near-surface mounted (NSM) reinforcement was recently introduced as a promising technique for strengthening of masonry walls and reinforced concrete members. Design guidelines for this technique are currently under consideration by the ACI Committee 440. NSM reinforcement technique consists of placing the FRP rebars or strips into grooves pre-cut into the concrete cover in the tension region of the reinforced concrete member and bonded to the three sides of the groove using high strength epoxy adhesive or cementitious grout. Application of NSM FRP reinforcement does not requires surface preparation work as in the case for externally bonded FRP reinforcement. Configuration of the FRP reinforcements used for NSM technique is controlled by the depth of the concrete cover. After installation, the NSM FRP reinforcements are protected against mechanical damage, wear, impact and vandalism from vehicles. The technique could also provide better fire resistance; therefore, it could reduce the cost of fire protection measures.

The objectives of this research program were to examine the structural performance of reinforced concrete beams strengthened in flexure with various NSM FRP reinforcements and compared with beams strengthened with externally bonded FRP reinforcement. The variables investigated were the type of fibres including carbon and glass, and the configuration of the FRP reinforcement including rebars and strips. The effectiveness of NSM FRP rebars and strips was examined and compared to externally bonded FRP strips using the same material and axial stiffness

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens and Set-Up

A total of eight, simply supported, 2.7 m long, concrete T-beams were constructed and tested under a monotonically increasing concentrated load applied at midspan of the beam using displacement-control mode at a loading rate of 1.07 mm/min. The test set-up of a T-beam specimen is shown in Figure 1. The bottom tension reinforcement consisted of 2#13 deformed steel bars of nominal diameter 12.7 mm running along the full length of the beams, and 2#16 deformed steel bars of nominal diameter 15.9 mm terminated with 90º bent at 100 mm away from the midspan section on both sides as shown in Figure 1. This arrangement of the bottom reinforcement was selected to ensure that the flexural failure of the strengthened beams will always occur at the midspan section, and to simulate field conditions where the bottom steel reinforcement is corroded or damaged. The top compression reinforcement consisted of 2#13 deformed steel bars of nominal diameter 12.7 mm. Shear reinforcement consisted of double-legged steel stirrups #13 deformed steel bar of nominal diameter 12.7 mm uniformly spaced at 100 mm centre-to-centre. The top flange was reinforced with a welded wire fabric mesh 51×51 MW5.6×MW5.6. Reinforcement details of a T-beam specimen are shown in Figure 1. The beams were instrumented, as shown in Figure 1, to measure applied load, deflection, strain in the concrete and in the FRP reinforcement during testing.

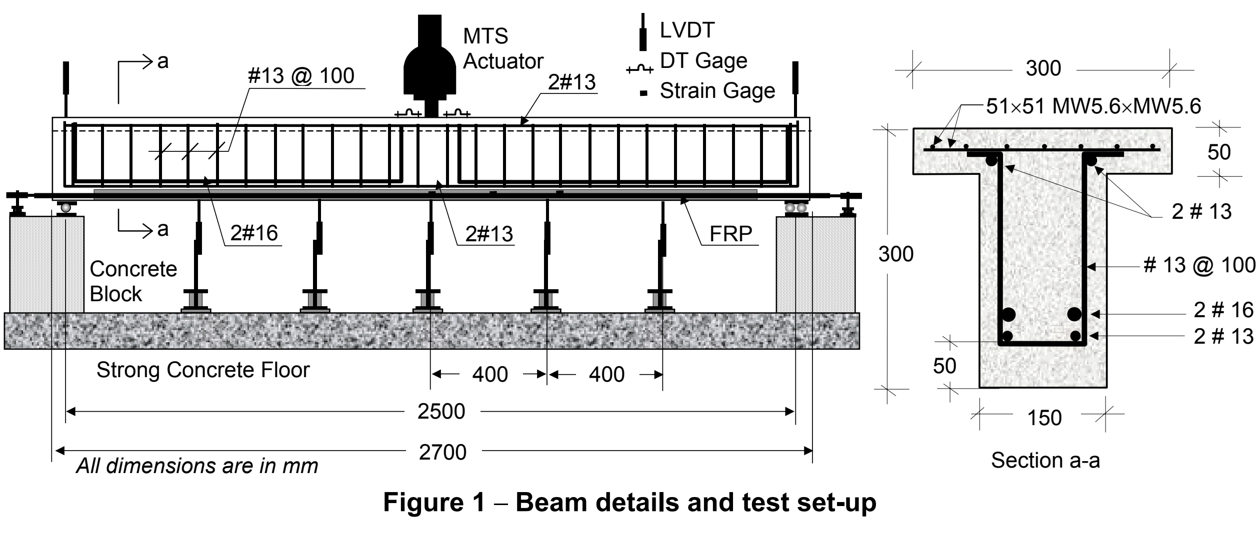

Figure 1 – Beam details and test set-up

2.2 Test Matrix and FRP Strengthening Systems

One beam was tested without strengthening (B0) and served as control specimen for comparison purposes to evaluate the improvement in flexural strength provided by the various NSM and externally bonded FRP reinforcements. Four beams (B1, B2, B3, and B4) were strengthened with different NSM FRP systems using Carbon Fibre-Reinforced Polymer (CFRP) rebars, two types of unidirectional pultruded CFRP strips, and unidirectional pultruded thermoplastic GFRP strips. Three beams (B2a, B3a, and B4a) were strengthened with externally bonded CFRP and GFRP strips. A summary of these beams is given in Table 1. The material properties of the different FRP strengthening systems are given in Table 2. The embedment lengths of all the NSM FRP rebar and strips and the length of the externally bonded FRP strips were kept constant in all beams as 2400 mm. The same axial stiffness, $(EA)_{FRP}$, for all FRP reinforcement was kept constant, hence according to the classical beam theory the load-deflection behavior of all strengthened beams is anticipated to be identical, where E and A are the modulus of elasticity and the area of the FRP reinforcement, respectively.

Table 1 – Test matrix for the T-Beam specimens

Beam #	FRP Strengthening System
B0	No strengthening
B1	One 9.5mm NSM CFRP rebar (a)
B2	Two 2mm×16mm NSM CFRP strips type 1(a)
B3	Two 1.2mm×25mm NSM CFRP strips type 2 (b)
B4	Five 2mm×20mm NSM GFRP thermoplastic strips (c)
B2a	Two 2mm×16mm Externally Bonded CFRP strips type 1 (a)
B3a	Two 2mm×16mm Externally Bonded CFRP strips type 2 (b)
B4a	Five 2mm×20mm Externally Bonded GFRP thermoplastic strips (c)

(a) Hughes Brothers, (b) Structural Composite, (c) Dow Plastics Chemical

Table 2 – FRP material mechanical properties as reported by the manufacturer

FRP products (***Manufacturer***)	**Dimensions (mm)**	**Area *A* (mm^2)**	**Elastic Modulus *E* (GPa)**	**Ultimate Tensile Strength (MPa)**	**Ultimate Tensile Strain (%)**
Aslan 200 CFRP rebar (*Hughes Brothers*) [2]	9.5	71.3	122.5	1408	1.14
Aslan 500 CFRP strip* (*Hughes Brothers*) [2]	2 ×16	32	140	1525	1.08
Laminate CFK 150/2000 strip** *(Structural Composite Inc.)* [3]	1.2 × 25	30	150	2000	1.33
Thermoplastic GFRP strip (*Dow Plastics Chemical*) [4]	2 × 20	40	45	1000	2.22

* *Type* 1 **Type 2*

2.3 Installation of the FRP Reinforcements

Installation of the NSM FRP rebar and strips begins by making a series of grooves, cut into the concrete cover in the longitudinal direction at the tension side of the beam specimens, with different cross sections depending on the type of FRP reinforcements used as shown in Figure 2. Each groove was filled completely with the epoxy adhesive paste. Then, the FRP reinforcements were inserted inside the grooves ensuring that they were completely covered with epoxy and lightly pressed to displace the bonding agent. Note that for the five NSM GFRP strip, three grooves were cut in which one GFRP strip was inserted into the middle groove, and two strips bonded together side by side were placed in each of the outer two grooves. For the externally bonded strips, a U-shaped wrap CFRP sheet with 100 mm width was placed around the web of the concrete beams at the both ends of the FRP strips, with the direction of the fibres perpendicular to the longitudinal axis of the member, to improve the anchorage of the FRP strengthening system. The epoxy adhesive was allowed to fully cure at room temperature for at least one week before testing of the beams.

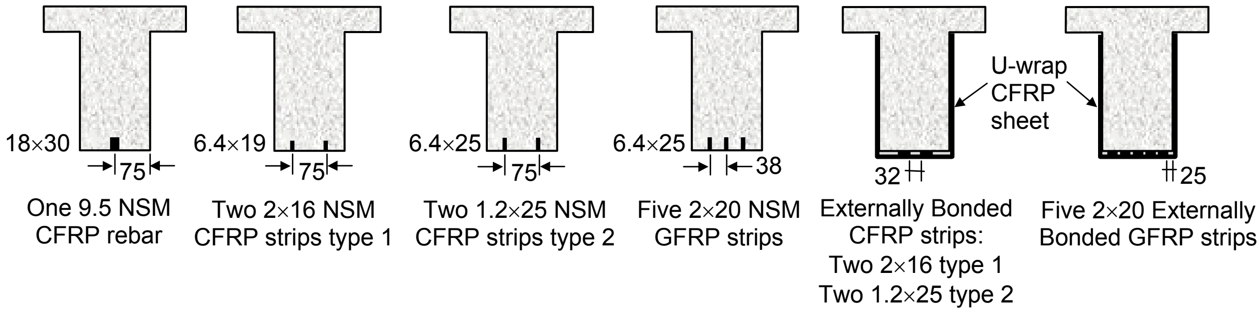

Figure 2 – FRP strengthening schemes

3. TEST RESULTS AND DISCUSSION

3.1 Effectiveness of NSM CFRP Rebar and Strips

The load-midspan deflection behaviour of the strengthened beams is shown in Figure 3. Prior to cracking, the flexural behaviour for all strengthened beams was similar to that of the unstrengthened beam. This behavior indicates that using NSM FRP reinforcements did not contribution to increase the stiffness and strength in the elastic range. However, after cracking the flexural stiffness and strength of the strengthened beams with NSM FRP reinforcements were significantly improved compared to the unstrengthened beam. After cracking, a nonlinear behavior was observed up to failure.

In general, the behavior of the strengthened beams indicated significant increase in the stiffness and strength in comparison with the unstrengthened beam. Using the same axial stiffness of CFRP reinforcement, an increase in the ultimate strength of 69, 79, and 99 percent were measured for beams B1, B2, and B3, respectively. The significant increase, in the ultimate load carrying capacity, of beam B3 strengthened with NSM CFRP strips (type 2) when compared with beam B2 strengthened with NSM CFRP strips (type 1) is due to the high ultimate tensile strength of the material used in this case as well due to the smaller thickness of the strips type 2 than strips type 1 which reduces the risk of delamination. Beam B1 with NSM CFRP rebar showed the smaller increase in strength due to the early debonding of the CFRP rebar at failure as well the smaller bonding surface of the NSM CFRP rebar with respect to the NSM CFRP strips (type 1 and type 2).

Using NSM FRP reinforcement resulted in significant reduction of the deflection and crack widths as well delayed formation of new cracks in the strengthened beams. The formation of cracks followed a typical crack pattern of flexural members. Failure of beam B1 was due to splitting of the epoxy cover in the groove followed by complete debonding of the rebar at the CFRP-epoxy interface and cracking of the concrete surrounding the epoxy in the groove as shown in Figure 4. After debonding, the load dropped to a load level equivalent to the measured yielding load and the deflection kept on increasing until failure occurred due to crushing of the concrete in the compression zone, then the test was stopped. The debonding initiated at the concrete section where 39 percent of the bottom flexural reinforcement was terminated (Figure 1). Splitting of the epoxy is the result of high tensile stresses at the CFRP rebar-epoxy interface. To reduce the induced tensile stresses at the FRP-epoxy interface, the thickness of the epoxy cover must be increased and/or high tensile adhesive must be used to shift the location of failure to the concrete-epoxy interface. Increasing the thickness of the adhesive will reduce the shear deformation within the adhesive layer and therefore results in a significant increase in debonding loads. Failure of beams B2 and B3 was due to rupture of the NSM CFRP strips at midspan as shown in Figure 4. After rupture of the NSM CFRP strips, the load dropped to a load level equivalent to the yielding load of the cross-section and the beam behaved as conventional concrete beams reinforced with steel bars.

At failure, the maximum measured tensile strain in the NSM CFRP rebar prior to debonding was 0.88 percent which is 77 percent of the rupture strain of the CFRP rebar. The maximum measured tensile strain in the CFRP strips type 1 and type 2 at failure for beams B2 and B3 were 1.34 and 1.38 percent, respectively indicating full utilization of the tensile strength of the two types of CFRP strips used.

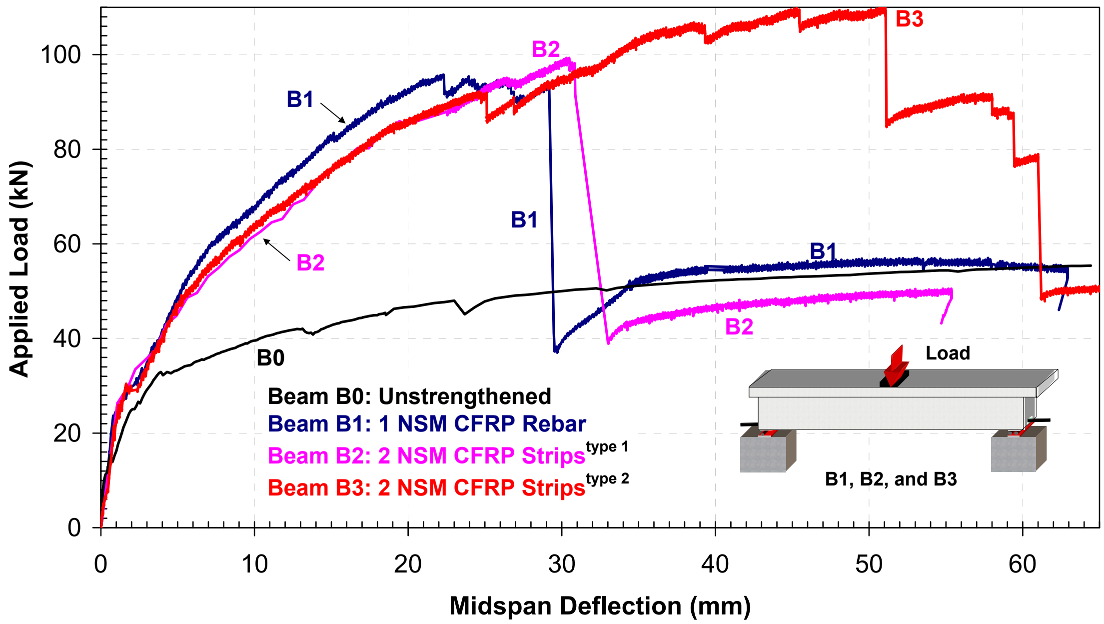

Figure 3 – Load-midspan deflection of beams strengthened with NSM CFRP rebar and strips

Figure 4 – Failure of beams strengthened with NSM CFRP rebar and strips type 1 and type 2

Table 3 – Summary of significant test results

Strengthening Scheme	Beam #	P_{cr} (Kn)	Δ_{cr} (mm)	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)	ε_u (%)	Failure Mode	% increase in P_u
—	B0	21.98	1.35	38.11	8.88	55.4	64.4	—	(A)	—
Near-Surface Mounted FRP	B1	24.7	1.27	47.94	4.85	93.8	29.2	0.88	(B)	69.3
	B2	22.24	1.08	48.62	5.61	99.3	30.5	1.34	(C)	79.2
	B3	30.11	1.702	49.16	5.25	110.2	50.8	1.38	(C)	98.9
	B4	24.46	1.6	48.17	5.67	102.7	44.3	1.35	(D)	85.4
Externally Bonded FRP	B2a	22.46	1.22	44.88	4.42	64.6	43.7	0.48	(E)	16.6
	B3a	22.24	1.25	61.0	6.98	69.3	16.3	0.42	(E)	25.1
	B4a	29.13	0.95	48.16	4.39	71.1	22.2	0.62	(F)	28.3

P_{cr} : cracking load
Δ_{cr} : midspan deflection at cracking
P_y : yield load
Δ_y : midspan deflection at yielding
P_u : ultimate failure load
Δ_u : midspan deflection at failure
ε_u : maximum tensile strain in the FRP rebar or strip at failure

Failure Mode Description

(A) Crushing of concrete and steel yielding
(B) Debonding of the NSM CFRP rebar (epoxy split failure)
(C) Rupture of the NSM CFRP strips
(D) Debonding of the NSM GFRP strips (concrete split failure)
(E) Debonding of the Externally Bonded CFRP strips
(F) Debonding of the Externally Bonded GFRP strips

3.2 NSM vs. Externally Bonded CFRP Strips

Beams B2a and B3a, strengthened with externally bonded CFRP strips type 1 and type 2, respectively exhibited similar behavior to that of the control-unstrengthened beam (B0) up to cracking. This behavior indicates that using externally bonded FRP reinforcements did not contribute significantly to the stiffness and strength in the elastic range. After cracking, the load-deflection response of the beam strengthened with externally bonded CFRP strips followed the same behaviour of beams strengthened with NSM CFRP strips up to yielding of the flexural reinforcement as shown in Figure 5. After yielding of the internal steel reinforcement, and under further increase of the applied load, the cracks continued to widen and failure occurred due to debonding of the externally bonded strips as shown in Figure 6.

Using the same axial stiffness, $(EA)_{FRP}$, of the CFRP strips used as NSM for beams B2 and B3, externally bonded CFRP strips increased the strength by only 16.6 and 25 percent for beams B2a and B3a compared to the unstrengthened beam due to debonding failure of the externally bonded strips from the concrete surface. However, the NSM CFRP strips increased the strength by 79 and 99 percent for beams B2 and B3 as shown in Figure 5. The strength increase using the same CFRP strips as NSM was about 4.8 and 4.0 times that obtained using externally bonded strips for beams B2 and B3. Thus, the NSM strengthening technique using CFRP strips is more effective in comparison to externally bonded one.

At the onset of delamination, the maximum measured tensile strain in the externally bonded CFRP strips was 0.48 and 0.42 percent for beams B2a and B3a. This represents only 44 and 32 percent of the rupture strain reported by the manufacturer for the CFRP strips, therefore, the externally bonded strengthening system did not utilize the full tensile strength of the CFRP strips.

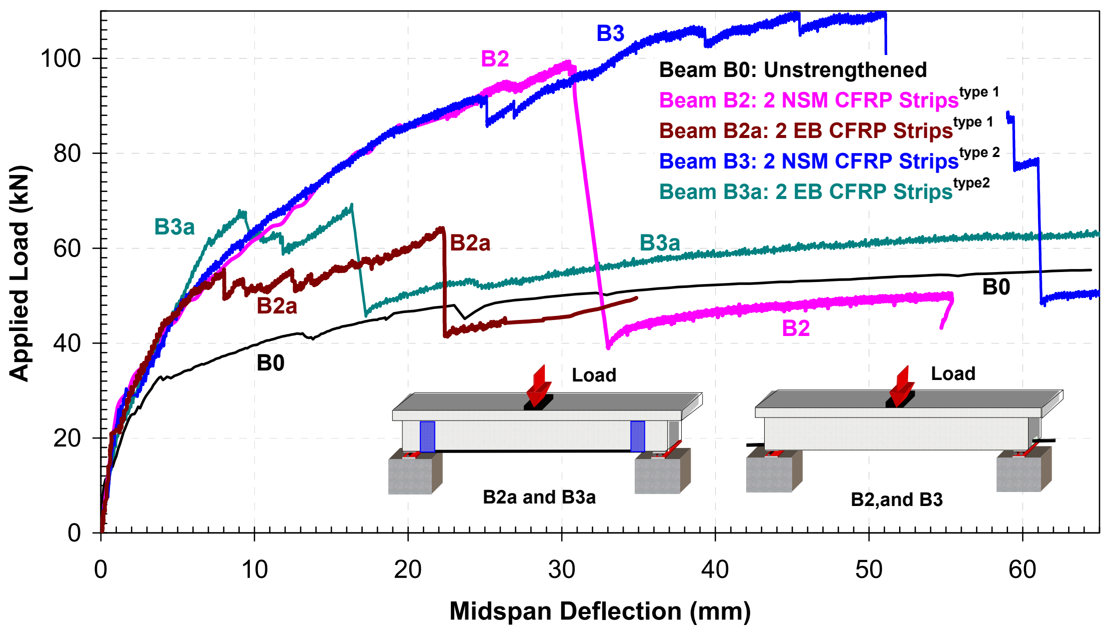

Figure 5 – Load-midspan deflection of beams strengthened with NSM and EB CFRP strips

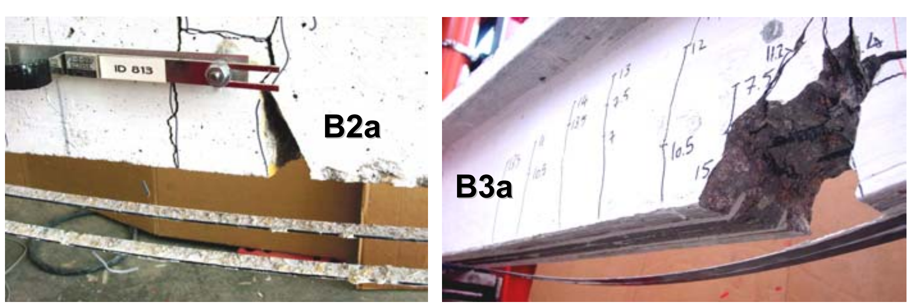

Figure 6 – Debonding failure of beams strengthened with EB CFRP strips type 1 and type 2

3.3 Effect of Material Type of Fibre

Beam B4, strengthened with GFRP thermoplastic strips as NSM reinforcement, exhibited significant enhancement in strength and stiffness in comparison to the unstrengthened beam as shown in Figure 7. An increase in the ultimate strength of 85 percent was observed. The ultimate load carrying capacity of beam B4a strengthened using externally bonded thermoplastic GFRP strips increased by 28 percent.

Failure of beam B4 was due to cracking of the concrete surrounding the epoxy in the groove which occurred at the concrete-epoxy interface known as “concrete split failure” as shown in Figure 8. Debonding started to occur at the location where 39 percent of the bottom steel reinforcement were terminated as shown in Figure 1. This failure is the result of the high shear stress concentration in this zone as discussed before. Debonding of the concrete and the split failure occurred when the tensile stresses at the concrete-epoxy adhesive interface reached the tensile strength of concrete. This failure mode is greatly influenced by the groove dimensions as well as the mechanical characteristics of the materials [5]. Debonding extended as a horizontal splitting crack along the concrete cover towards the ends of the beam. Under further increase of the applied load, the horizontal split crack became wider and extended into the end of the NSM GFRP strips causing severe cracking in the concrete cover. At the onset of failure, the load dropped to the yielding load level of the beam cross-section and the deflection kept on increasing until failure occurred due to crushing of the concrete in the compression zone. After complete failure, the concrete cover to the internal steel separated from the steel. It was observed that the NSM GFRP strips had adhered well to the concrete of the strengthened beam. The amount of concrete adhered to the GFRP strips varied considerably. In examining the concrete surface of the failed member, aggregate pullout was noted without any sign of damage of the NSM GFRP strips.

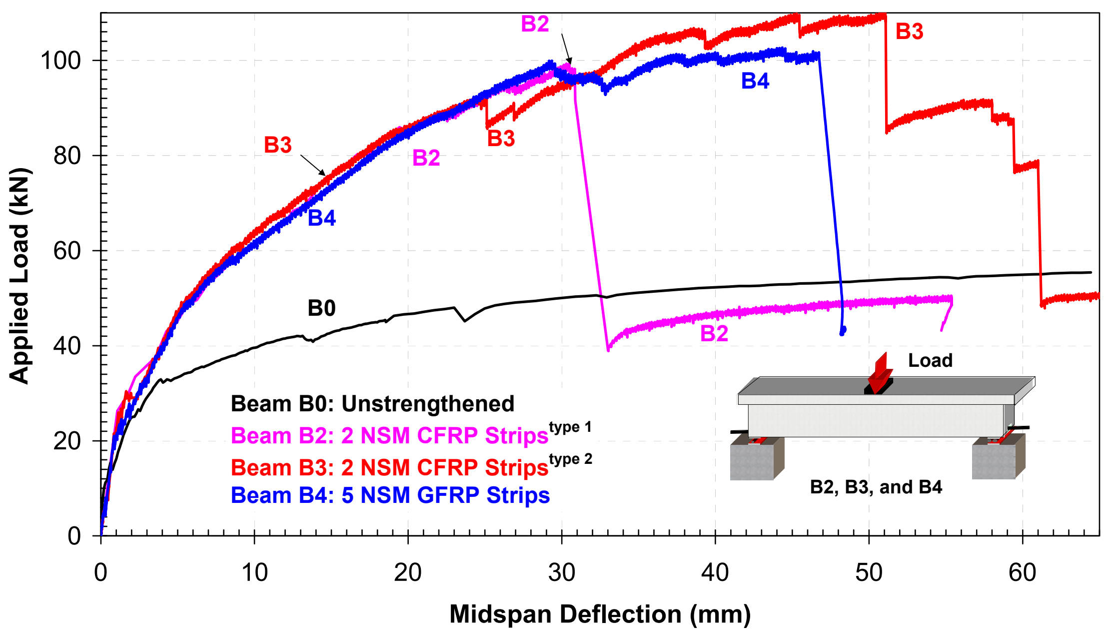

Figure 7 – Load-midspan deflection of beams strengthened with NSM CFRP and GFRP strips

Figure 8 – Debonding failure of beam B4 strengthened with five NSM thermoplastic GFRP strips

As presented earlier, failure of the NSM CFRP strips (types 1 and 2) occurred by rupture of the strips when the strain in the strips reached the ultimate tensile strain capacity reported by the manufacturers (1.12% for CFRP type 1, and 1.34% for CFRP type 2). These ultimate strain capacities are significantly less than the 2.2% ultimate tensile strain capacity of the GFRP thermoplastic strips as reported by the manufacturer. Since the GFRP thermoplastic strips possess large ultimate strain capacity, and because the thickness of the epoxy in the outer grooves was almost half that of the epoxy in the middle groove failure was dominated by the higher shear stresses at the concrete-epoxy interface. Therefore, increasing the thickness of the epoxy (i.e. increasing the groove size) will reduce the shear stresses at the concrete-epoxy interface and could results in an increase in debonding load.

4. CONCLUSIONS

The effectiveness of using near-surface mounted FRP rebars or strips for strengthening concrete beams has been illustrated. The following conclusions can be drawn from the experimental results:

1. Using the same axial stiffness of FRP to strengthen reinforced concrete beams, the beams strengthened with NSM FRP reinforcement achieved higher ultimate load than beams strengthened with externally bonded FRP reinforcement. This is due to the high utilization of the tensile strength of the FRP reinforcement. The NSM FRP strips have double the bond area compared to externally bonded FRP strips. Should be noted that the thickness could affect the debonding phenomena.
2. The ultimate strength of the strengthened beams with NSM CFRP strips was governed by the tensile rupture strength of the strips. Full composite action between the NSM strips and concrete was achieved.
3. FRP-epoxy-split failure was the dominant mode of failure for the beam strengthened with NSM CFRP rebar as a result of high tensile stresses at the CFRP rebar-epoxy interface.
4. Concrete-split failure was the governing mode of failure for the strengthened beam with NSM GFRP thermoplastic strips.
5. Failure of beams strengthened with externally bonded CFRP or thermoplastic GFRP strips was due to debonding between the strips and the concrete at a load level significantly lower than the beams strengthened with NSM CFRP rebar or strips and NSM GFRP thermoplastic strips.
6. Strengthening a concrete beam with NSM CFRP rebar provided considerable less increase of the load carrying capacity compared to similar beams strengthened with NSM CFRP strips with the same axial stiffness due to possible early debonding failure that occurred at the CFRP rebar-epoxy interface as well to the smaller bonding surface of the NSM CFRP rebar with respect to the NSM CFRP strips.

In summary, the NSM FRP strengthening technique could be considered as a valid alternative to externally bonded FRP strengthening system.

5. ACKNOWLEDGEMENT

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