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Modelling of Reinforced Concrete Flexural Members Strengthened with Near-Surface Mounted FRP Reinforcement

by R. El-Hacha, S.H. Rizkalla, and R. Kotynia

Synopsis: This paper presents an analytical investigation conducted to study the flexural behavior of reinforced concrete beams strengthened with various Near-Surface Mounted (NSM) Fiber-Reinforced Polymers (FRP) reinforcements. The materials used in this investigation included carbon-fiber-reinforced-polymer (CFRP) rebars and strips, and glass fiber-reinforced-polymer (GFRP) rebars and strips. The analysis included the effects of strengthening on the serviceability and ultimate limit states as well the effect of tension stiffening. The effectiveness of NSM FRP rebars and strips was examined and compared to externally bonded (EB) FRP strips and sheets using the same material type and axial stiffness. Results from the analytical models were compared with those obtained from experimental studies. The analytical results agree very well with those obtained from the experimental results. It was found that the analytical model could effectively simulate the behaviour of the reinforced concrete beams strengthened with various NSM FRP and EB FRP reinforcements. 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 EB FRP reinforcement. This result is due to the high utilization of the tensile strength of the FRP reinforcement.

Keywords: carbon; externally bonded; fiber-reinforced polymers; glass; near-surface mounted; rebars; reinforced concrete beam; strengthening; strips

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INTRODUCTION

Fiber-Reinforced Polymers (FRP) materials have been used extensively, in different configurations and techniques, in the last decade for strengthening bridges and buildings. Externally bonded (EB) FRP sheets and strips are currently the most commonly used technique for flexural and shear strengthening of concrete beams and slabs. This method of strengthening has been the subject of extensive experimental investigations, and codes and design guidelines/manuals have been published that address many aspects of this technology. Several researchers reported that the failure of concrete members strengthened with EB FRP sheets or 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]. An innovative area of this work that is emerging is the use of prestressed FRP sheets for strengthening structures. By applying a prestress to the FRP sheets or strips, the material may be used more efficiently since a greater portion of its tensile capacity is engaged. Several systems have been developed to induce a prestress in the FRP sheets or strips for flexural strengthening [1]. However, EB FRP sheets and strips could be highly susceptible to damage from collision, fire, temperature, ultraviolet rays, and moisture absorption [2]. In some cases, insufficient protection may reduce the service life of the structure. To minimize these problems, to improve utilization of the FRP materials, and to ensure long service life for the selected system, near-surface mounted (NSM) reinforcement was recently introduced as a promising strengthening technique and a valid alternative to the EB FRP technique for increasing flexural strength of reinforced concrete members [3,4,5,6,7]. The NSM technique consists of placing the FRP reinforcing rebars or strips into grooves precut into the concrete cover in the tension side of the strengthened concrete member filled with high-strength epoxy adhesive. This method is relatively simple and considerably enhances the bond of the FRP reinforcements, thereby using the material more effectively. Configuration of the FRP reinforcements used for the NSM technique is controlled by the depth of the concrete cover.

Over the past few years, a number of researchers have studied the behavior and modeling of reinforced concrete members strengthened with EB FRPs. Published literature on the use of NSM FRP rebars and strips for structural strengthening is very limited when compared with that of EB FRP sheets and strips. Design guidelines for the NSM FRP strengthening technique are currently under consideration by ACI Committee 440 for the coming version of the "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-02)."

RESEARCH SIGNIFICANCE

This paper presents an analytical investigation conducted to study the structural performance of reinforced concrete beams strengthened in flexure with various Near-Surface Mounted (NSM) Fiber-Reinforced Polymers (FRP) reinforcements. The effectiveness of NSM FRP rebars and strips was examined and compared to externally bonded (EB) FRP strips and sheets using the same material type and axial stiffness. The variables investigated were the type of fibers including carbon-fiber-reinforced-polymer (CFRP) and glass fiber-reinforced-polymer (GFRP), and the configuration of the FRP reinforcement including rebars, strips and sheets. The analysis included the effects of strengthening on the serviceability and ultimate limit states as well the effect of tension stiffening. Results from the analytical models were compared with those obtained from experimental studies [5,6].

EXPERIMENTAL INVESTIGATION

Test Specimens and Set-up

A total of ten, simply supported, concrete T-beams were constructed and tested under a monotonic 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. Details of the test specimens can be found in El-Hacha and Rizkalla (2004).

Test Matrix and FRP Strengthening Systems

One beam was tested without strengthening (B0) and served as a control specimen for comparison purposes to evaluate the improvement in flexural strength provided by the various NSM and externally bonded FRP reinforcements. Five beams (B1, B2, B3, B4, and B5) were strengthened with different NSM FRP systems using Carbon Fiber-Reinforced Polymer (CFRP) rebars [7], Glass Fiber-Reinforced Polymer (GFRP) rebars[7], two different types of unidirectional pultruded CFRP strips [8,9], and unidirectional pultruded thermoplastic GFRP strips [9]. Four beams (B2a, B3a, B4a, and B5a) were strengthened with externally bonded CFRP strips [8,9], GFRP strips [10], and CFRP sheets [11]. A summary of these beams is given in Table 1. The various FRP strengthening systems are shown in Figure 2. The material properties of the different FRP reinforcements are given in Table 2 as reported by the manufacturers with linear stress-strain behavior up to failure. The embedment lengths of all NSM FRP rebars 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 reinforcements 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.[5,6]

Installation of the NSM and EB FRP Reinforcements

Installation procedure of the various NSM FRP rebars and strips and the EB FRP strips and sheets can be found in El-Hacha and Rizkalla (2004).

Test Results

A comprehensive discussion on the effectiveness of NSM CFRP rebar versus NSM CFRP strips, the effectiveness of NSM strips versus EB CFRP strips, and the effect of material type of fiber (CFRP strips versus GFRP strips) has been reported in details by El-Hacha and Rizkalla (2004) and El-Hacha et al. (2004). However, the experimental results of the beam strengthened with NSM GFRP rebars and the beam strengthened with EB CFRP sheets have not been reported elsewhere. Therefore, a brief summary of the experimental test results is reported in this paper. The comparison is presented by the experimental load-midspan deflection curves shown in Figures 3 and 5 for the beams strengthened with various NSM FRP reinforcements and the beams strengthened with various EB FRP reinforcements, respectively. Figures 4 and 6 show the experimental load versus tensile strain at midspan in the NSM FRP reinforcements and the EB FRP reinforcements, respectively. A Summary of significant test results and the failure mode of all tested beams are given in Table 3, and is presented briefly hereafter:

1. The beams strengthened with various NSM FRP reinforcements achieved higher ultimate load than the beams strengthened with various EB FRP reinforcements having the same axial stiffness of FRPs. This is due to the high utilization of the tensile strength of the FRP reinforcement.
2. The beams strengthened with NSM CFRP strips failed by tensile rupture of the strips.
3. The beams strengthened with NSM CFRP and GFRP rebars failed by debonding at the FRP- epoxy interface.
4. For the beam strengthened with NSM GFRP strips, failure was dominated by the high shear stresses at the concrete-epoxy interface.
5. All beams strengthened with EB FRP strips and sheets failed by debonding between the FRP and the concrete.
6. In general, the behavior of the NSM strengthened beams indicated significant increase in the stiffness and strength in comparison with the EB strengthened beams as well the unstrengthened beam.
7. In summary, the NSM FRP strengthening technique could be considered as a valid alternative to EB FRP strengthening technique.

ANALYTICAL MODELLING

A non-linear iterative analytical model [12] of one-dimensional members based on principles of equilibrium of forces, strain compatibility, and representative material stress-strain properties for the concrete, steel and FRPs was used to predict the overall flexural behavior of the unstrengthened and strengthened concrete beams with the various NSM and EB FRP reinforcements. The model considers the non-linear behavior of the concrete, tension stiffening is included in the analysis to account for the contribution of the tensile strength of concrete. This analytical model has been verified and compared very well with the test results of reinforced concrete beams externally strengthened by non-prestressed [13,14] and prestressed CFRP strips [15].

The analysis of the concrete beams was performed using simple plane section analysis. The model was based on the layer-by-layer approach to evaluate the sectional forces corresponding to a given strain distribution at a specific section (Figure 7 (a)). The stress-strain relationships for concrete, steel and various FRPs are shown in Figures 7 (b and c).

The load-midspan deflection was determined from the predicted moment-curvature responses at different sections of the beam by integrating the curvature along the beam. For the strengthened beams, the FRP reinforcements at the bottom face of the beam are considered as a layer of tension reinforcement with linear stress-strain relationship up to failure. External load value was calculated based on the equilibrium condition of generalized forces in the cross-section. Load at which limit strain in one of the materials is reached (ε_{cu} of concrete, ε_{su} of steel, ε_f of the EB CFRP strip and the NSM CFRP strip prior delamination or debonding failure) was accepted as the load bearing capacity of the cross-section. Table 4 gives an overall comparison between the analytical and experimental results. Note that only the experimental results of the beams strengthened with various NSM FRP reinforcements are compared with the analytical results as shown in Figures 8 and 9. The analytical and experimental results are in good agreement.

The deflections at midspan at the centre of the bottom face of the concrete beams were measured using linear variable displacement transducers (LVDTs). The model was used to predict the load-midspan deflection for the control unstrengthened beam and compared very well with the experimental curve in both the linear (prior to concrete cracking) and nonlinear ranges as shown in Figure 8. Comparisons between the predicted load-midspan deflection curves and those measured in the tests are shown in Figure 8 for all strengthened beams with various NSM FRP reinforcements. In general, the predicted load-midspan deflection curves agreed very well with the experimental results and followed the same path. However, after yielding of the internal reinforcing steel, the analytical load-midspan deflection curves were stiffer than the experimental curves. This could be attributed to several effects such as the assumption of perfect bond between the internal reinforcing steel and the concrete, and between the FRP and concrete assumed in the analytical model where some slip takes place in the experimental beams. As such bond slip occurs, the perfect composite action between the reinforcing steel and concrete is reduced and the overall stiffness of the experimental load-midspan deflection of the beams is expected to be lower than for the analytical model.

The tensile measured strains in the NSM FRP reinforcements at midspan were monitored during testing using electrical resistance 120 ohms strain gauges. Comparison between the predicted load-tensile strain in the various FRP reinforcements at midspan and those measured in the tests are shown in Figure 9 for all strengthened beams. The comparison between the predicted and experimental curves shows good agreement in both the linear (prior to concrete cracking) and nonlinear ranges.

As shown in Figures 4 and 6, during testing just prior to failure, some beams showed reversal strain in the FRP reinforcement that could be attributed most likely to a local effect caused by the major cracks close to midspan. The strain reversal could also be due to some sudden local delamination or debonding that preceded the failure as can be observed in the sudden drops of the applied load as shown in the experimental load-midspan deflection curves of the various strengthened beams with NSM FRP reinforcement (Figures 3 and 5). This behavior does not occur in the analytical model prediction as the effect of debonding or delamination was not taken into account. The maximum predicted NSM FRP tensile strains at failure in all strengthened beams were very close to the values obtained from the experimental results and confirmed the dominate failure modes observed in each of the strengthened beams during the test as shown in Table 3.

As can be seen that the experimental load-deflection and load-strain curves of all tested beams confirmed compatibility of the analytical model over the entire range of loads. Therefore, this model can be used for designing reinforced concrete members strengthened in flexure with NSM FRP reinforcements. The model may be applied in two different ways; the first method is based on the actual strength material characteristic of the concrete, steel and FRP reinforcement to determine the nominal moment capacity. The nominal moment is multiplied by a performance factor to give the design (ultimate) value. In the second method, the factored resistance moment (design load bearing capacity) is determined based on the design strength properties of all materials assessed using appropriate material resistance factors (partial safety factors) for concrete, steel and FRP reinforcement.

In general, the predicted load-midspan deflection and load-FRP tensile strain curves for the strengthened beams determined from the analytical model were in good agreement with the experimental results. In terms of the ultimate load and strain in the FRP at failure, the analytical results differ by less than 1% from the experimental results. The difference between the experimental and analytical curves is insignificant and could be considered within the range of experimental errors associated with physical constants (such as material properties such as, concrete was assumed homogeneous), physical variables (such as supports conditions, loading position, tolerance during fabrication and testing, depth of the internal steel and concrete cover), and errors in electronic measuring devices. The difference between the experimental and analytical curves could also be due to the assumption considered in the analytical model that perfect bond between the epoxy and the FRP reinforcement exists until failure.

CONCLUSIONS

The following conclusions can be drawn from this investigation:

- Strengthening concrete beams with NSM FRP reinforcements increased the flexural stiffness and the ultimate load carrying capacity of the strengthened beams compared to the unstrengthened beam and to the strengthened beams with externally bonded FRP reinforcement.
- For the beams strengthened with various NSM FRP reinforcements, the predicted load-midspan deflection curves agreed very well with the experimental results in both the linear (prior to concrete cracking) and non-linear ranges.
- The load-tensile strain curves for the various NSM FRP reinforcements showed good agreement between the experimental results and the prediction from the non-linear analytical model.
- Both the predicted load-midspan deflection and load-tensile strain in the various FRP reinforcements have similar trends with those obtained from the experimental results.
- The iterative non-linear analytical model used in this study demonstrated very well the behavior of the concrete beams and provided better understanding of the NSM FRP strengthened concrete beams.
- The analytical model can be used to conservatively estimate the load-carrying capacity of concrete beams strengthened with NSM FRP reinforcements. The model can be used to develop design guidelines for strengthening reinforced concrete beams with NSM and EB FRP reinforcements.

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REFERENCES

[1] El-Hacha, R., Wight, R.G., and Green, M.F., 2001, "Prestressed Fibre-Reinforced Polymer Laminates for Strengthening Structures." *Progress in Structural Engineering and Materials*, 2001:3, pp. 111-121.

[2] ACI Committee 440, 1996, "State-of-the-Art Report on Fiber Reinforced Plastic Reinforcement for Concrete Structures (440R-96) (Reapproved 2002)," American Concrete Institute, Farmington Hills, Mich., 68 p.

[3] De Lorenzis, L., Nanni, A., and La Tegola, A., 2000, "Flexural and Shear Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods," *Proceedings of the 3rd International Conference on Advanced Composite Materials in Bridges and Structures (ACMBS III)*, Ottawa, Ontario, Canada, Aug. 15-18, pp. 521-528.

[4] Hassan, T. K., 2002, "Flexural Performance and Bond Characteristics of FRP Strengthening Techniques for Concrete Structures," PhD thesis, University of Manitoba, Winnipeg, Manitoba, Canada, 304 p.

[5] El-Hacha, R.; Silva Filho, J. N.; Melo, G. S.; Rizkalla, S. H., 2004, "Effectiveness of Near-Surface Mounted FRP Reinforcement for Flexural Strengthening of Reinforced Concrete Beams," *Proceedings of the 4th International Conference on Advanced Composite Materials in Bridges and Structures (ACMBS IV)*, Calgary, Alberta, Canada, July 20-23, (CD-ROM), 8p.

[6] El-Hacha, R., and Rizkalla, S.H., 2004 "Near Surface Mounted FRP Reinforcements for Flexural Strengthening of Concrete Structures", *ACI Structural Journal*, Vol. 101, No. 5, September-October 2004, pp. 717-726.

[7] Kotynia R (2005) Effectiveness of Near Surface Mounted CFRP Reinforcement for Strengthening of Reinforced Concrete Structures, COBRAE Conference, Bridge Engineering with Polymer Composites, 30 March - 1 April 2005, EMPA, Dübendorf, Switzerland, 16 p.

[8] Hughes Brothers, "Aslan 200 CFRP Bars, and Aslan 500 CFRP Tape," Technical Information, http://www.hughesbros.com.

[9] Structural Composites Inc. (SCI), 2002, "Technical Guide for the Selection, Design and Installation of the En-Force FRP Systems", Waller, Texas, USA.

[10] Dow Plastics Chemical, 2000, "Fulcrum Thermoplastic Composite Technology," *Technical Data Sheet*, Dec., http://www.dowfulcrum.com.

[11] Master Builders Inc. 1996. MBrace/Forca Tow Sheet Technical Manual. Master Builders Inc., Cleveland, Ohio, USA.

[12] Czkwianianc, A., and Kaminska, M., 1993 "*Method of Nonlinear Analysis of One-dimensional Reinforced Concrete Members"*, *Proceedings of KILiW PAN IPPT*, Warsaw 1993, (in Polish), No 36, 130 pp.

[13] Kotynia, R., Kaminska, M., 2003, "Ductility and Failure Mode of RC Beams Strengthened for Flexure with CFRP", Report No. 13, Department of Concrete Structures, Technical University of Lodz, 2003, 51 pp.

[14] Kotynia R., 2003, Discussion (100-S5/From the January-February 2003, *ACI Structural Journal*), for paper by Sergio F. Breña, Regan M. Bramblett, Sharon L. Wood, and Michael E. Kreger, "Increasing Flexural Capacity of Reinforced Concrete Beams Using Carbon Fiber-Reinforced Polymer Composites". *ACI Structural Journal*, November-December 2003, pp. 355-357.

[15] Kotynia R., Stoecklin I., and Meier U. (2005) Prestressed and Gradually Anchored CFRP Strips for Strengthening Concrete Structures, *Proceedings of the 5th International Conference Analytical Models and New Concepts in Concrete and Masonry Structures*, Gliwice-Ustron, June 12 – 14, 2005 (accepted for publication).

Table 1 – Test Matrix for the T-Beam Specimens [5,6]

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)
B5	One 16.0mm NSM GFRP rebar (a)
B2a	Two 2mm×16mm Externally Bonded CFRP strips type 1 (a)
B3a	Two 1.2mm×25mm Externally Bonded CFRP strips type 2 (b)
B4a	Five 2mm×20mm Externally Bonded GFRP thermoplastic strips (c)
B5a	Two 0.165mm×120mm Externally Bonded CFRP sheets (d)

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

Table 2 – FRP Material Properties as Reported by the Manufacturers [8, 9, 10,11]

FRP products (*Manufacturer*)	**Dimensions (mm)**	**Area *A* (mm²)**	**Elastic Modulus *E* (GPa)**	**Ultimate Tensile Strength (MPa)**	**Ultimate Tensile Strain (%)**
Aslan 200 CFRP rebar (*Hughes Brothers*)	9.5	71.3	122.5	1408	1.14
Aslan 500 CFRP strip* (*Hughes Brothers*)	2 ×16	32	140	1525	1.08
Aslan 100 GFRP rebar (*Hughes Brothers*)	16.0	217.5	40.8	655	1.61
Laminate CFK 150/2000 strip** *(Structural Composite)*	1.2 × 25	30	150	2000	1.33
Thermoplastic GFRP strip (*Dow Plastics Chemical*)	2 × 20	40	45	1000	2.22
CFRP sheets (MBrace)	0.165×120	19.8	228	3790	1.66

* *Type* 1   ***Type 2*

Table 3 – Summary of Significant Experimental Results for all Beams [5,6]

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
Unstrengthened	B0	21.98	1.35	38.11	8.88	55.4	64.4	—	(A)	—
Near-Surface Mounted FRP Reinforcements	B1	24.70	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	1.70	49.16	5.25	110.2	50.8	1.38	(C)	98.9
	B4	24.46	1.60	48.17	5.67	102.7	44.3	1.35	(D)	85.4
	B5	21.16	1.04	61.56	7.05	110.0	54.6	1.21	(B)	98.6
Externally Bonded FRP Reinforcements	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
	B5a	18.00	2.03	62.37	11.55	77.9	24.2	0.62	(G)	40.6

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 (rebar-epoxy split failure)
(C) Rupture of the NSM CFRP strips
(D) Debonding of the NSM GFRP strips (concrete-epoxy split failure)
(E) Debonding of the Externally Bonded CFRP strips
(F) Debonding of the Externally Bonded GFRP strips
(G) Debonding of the Externally Bonded CFRP sheets

Table 4 – Comparison of Experimental and Analytical Results for the beams Strengthened with various NSM FRP Reinforcements

Strengthening Scheme	Beam #	Experimental					Analytical					Comparison	
		P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)	ε_u (%)	P_y (kN)	Δ_y (mm)	P_u (kN)	Δ_u (mm)	ε_u (%)	$\frac{P_{u,Exp}}{P_{u,Anl}}$	$\frac{\varepsilon_{u,Exp}}{\varepsilon_{u,Anl}}$
Unstrengthened	B0	38.11	8.88	55.4	64.4	—	40.0	6.10	55.4	64.4	—	1.00	—
Near-Surface Mounted FRP Reinforcements	B1	47.94	4.85	93.8	29.2	0.88	45.0	4.90	92.0	22.3	0.93	1.02	0.95
	B2	48.62	5.61	99.3	30.5	1.34	50.0	5.57	96.0	23.0	1.35	1.03	0.99
	B3	49.16	5.25	110.2	50.8	1.38	50.2	5.96	99.1	23.1	1.40	1.11	0.98
	B4	48.17	5.67	102.7	44.3	1.35	47.6	5.28	105.0	29.0	1.40	0.98	0.96
	B5	61.56	7.05	110.0	54.6	1.21	60.6	8.00	110.0	30.4	1.44	1.00	0.76

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

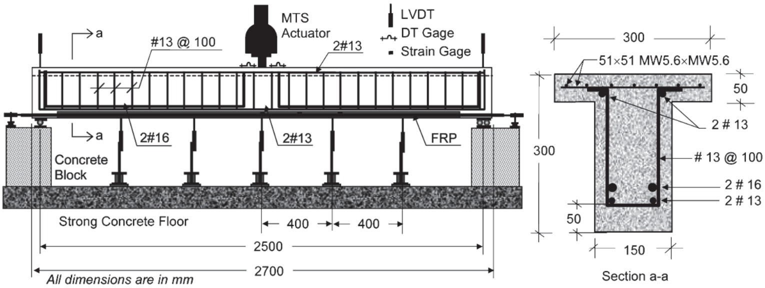

Figure 1 - Beam Details and Test Set-Up [6]

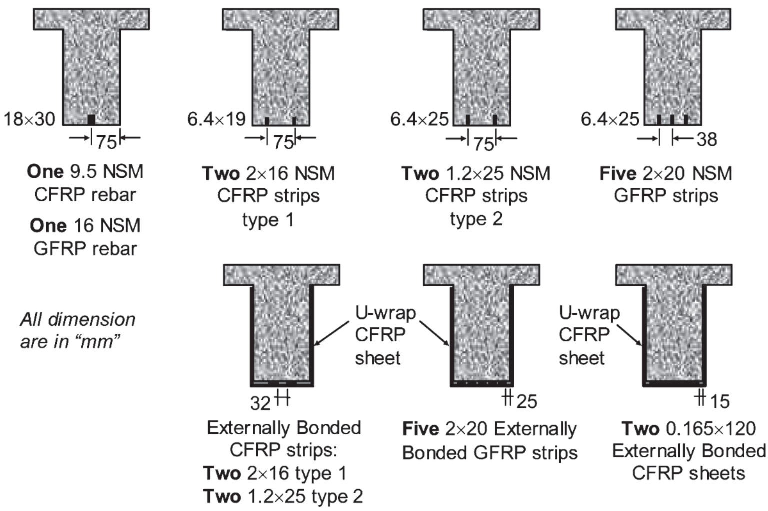

Figure 2 - Various FRP Strengthening Schemes

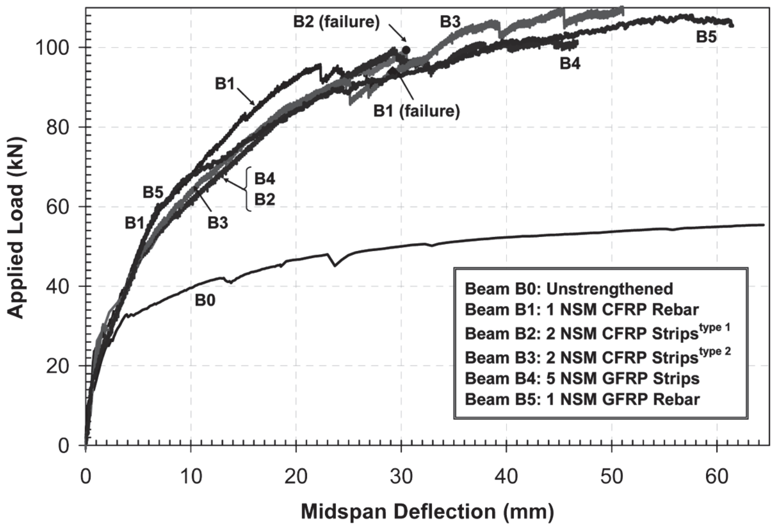

Figure 3 - Load - Midspan Deflection of the Beams Strengthened with various NSM FRP Reinforcements [5,6]

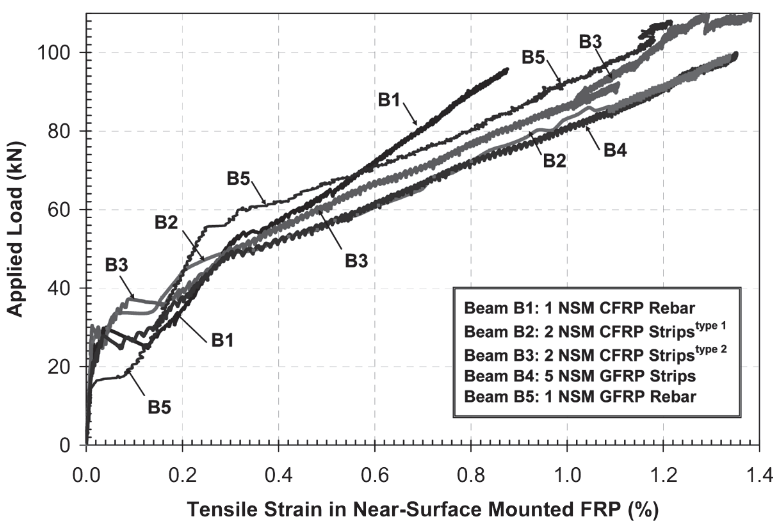

Figure 4 - Load - Tensile Strain in the various NSM FRP Reinforcements at Midspan for the Beams Strengthened with NSM FRP Reinforcements [5,6]

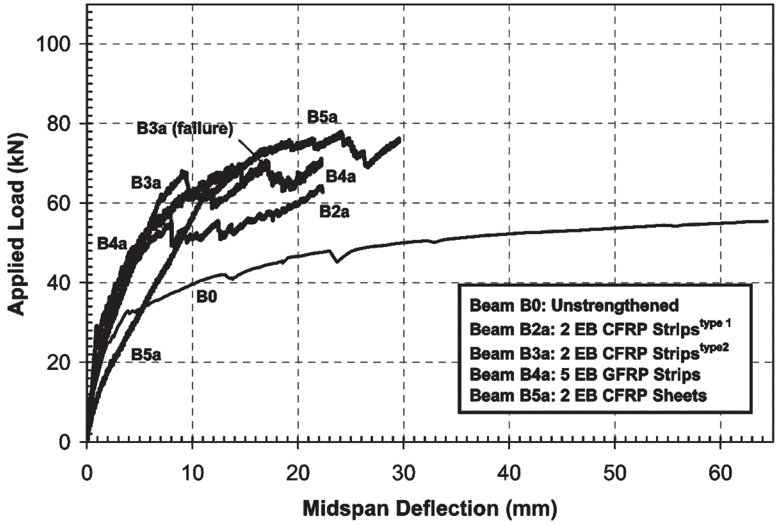

Figure 5 - Load-Midspan Deflection of the Beams Strengthened with various EB FRP Reinforcements [5,6]

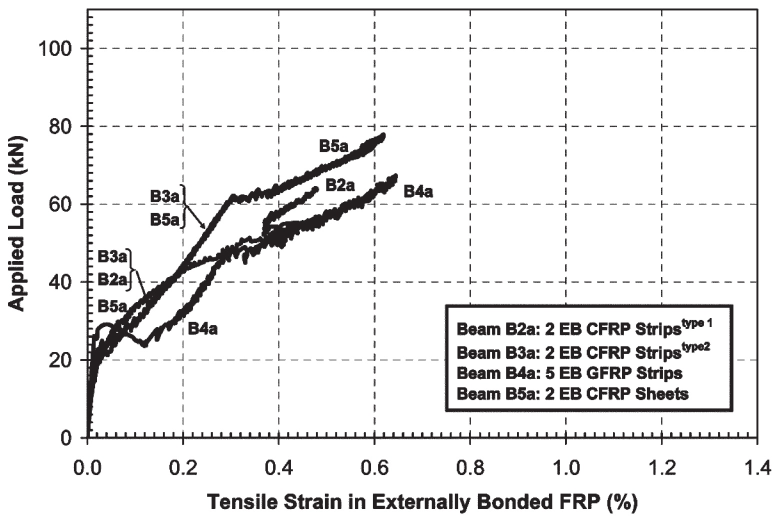

Figure 6 - Load-Tensile Strain in the various EB FRP Reinforcements at Midspan for the Beams Strengthened with EB FRP Reinforcements [5,6]

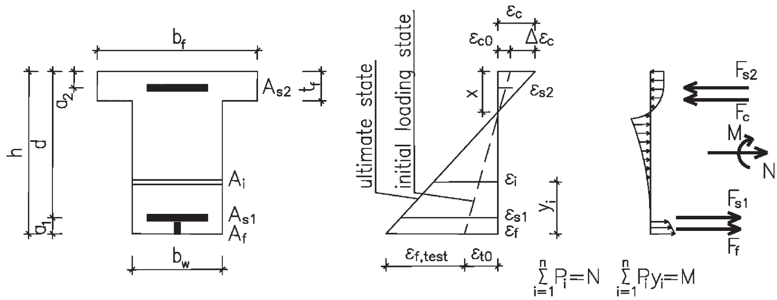

Figure 7 (a) - Calculation Model for a Specimen Strengthened with NSM FRP

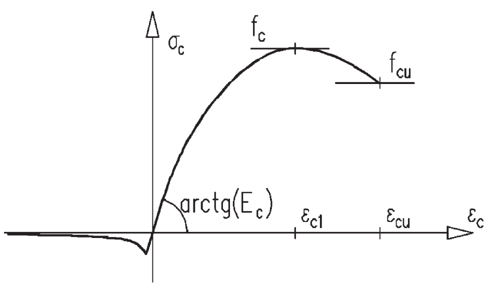

Figure 7 (b) - Stress-Strain Relationship for Concrete

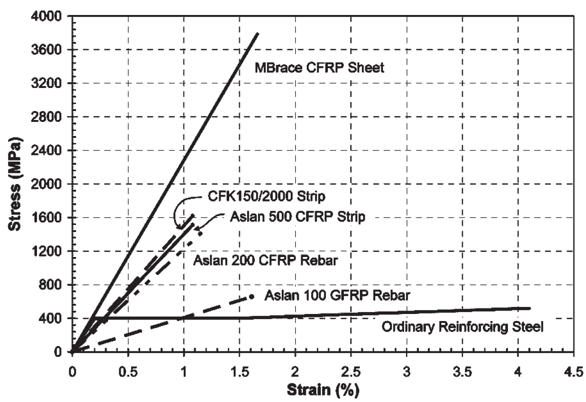

Figure 7 (c) - Stress-Strain Relationships for various FRP reinforcements and Reinforcing Steel

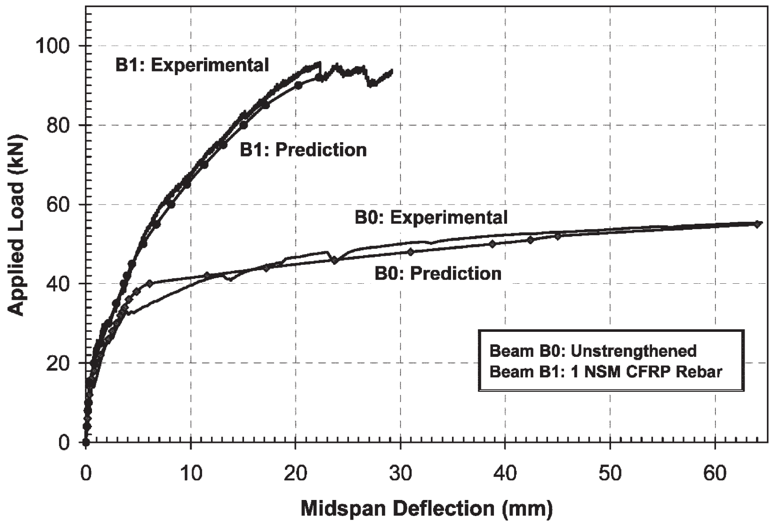

Figure 8 (a) - Load-Midspan Deflection Curves for Beams B0 and B1

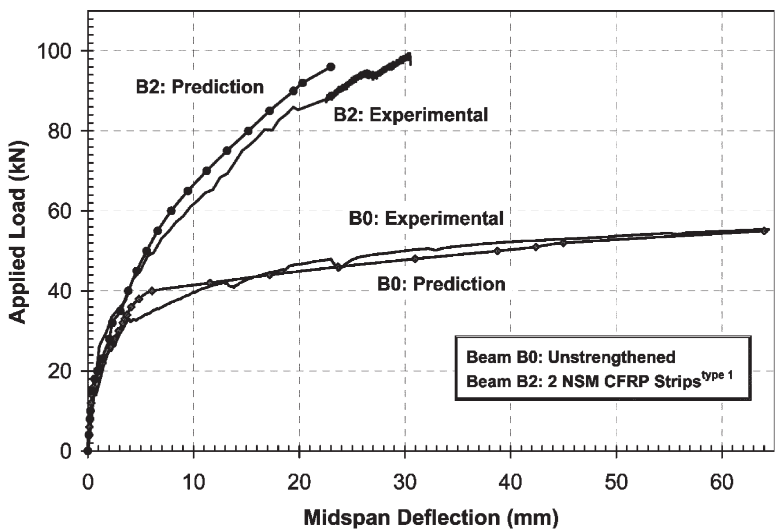

Figure 8 (b) - Load-Midspan Deflection Curves for Beams B0 and B2

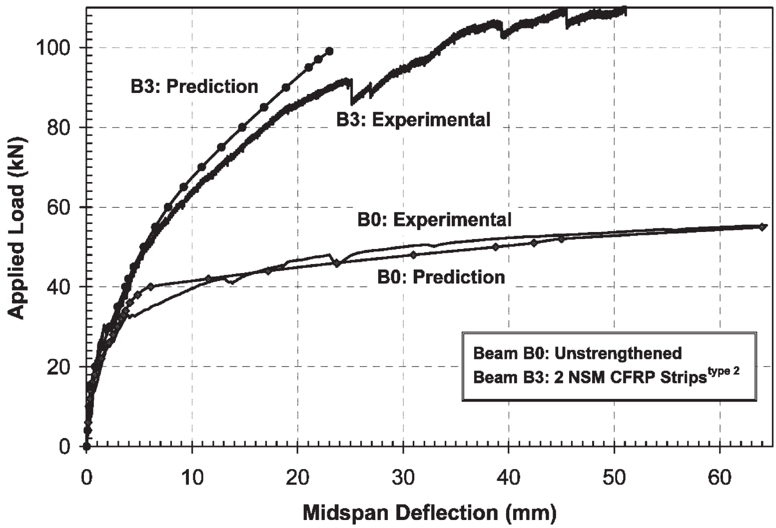

Figure 8 (c) - Load-Midspan Deflection Curves for Beams B0 and B3

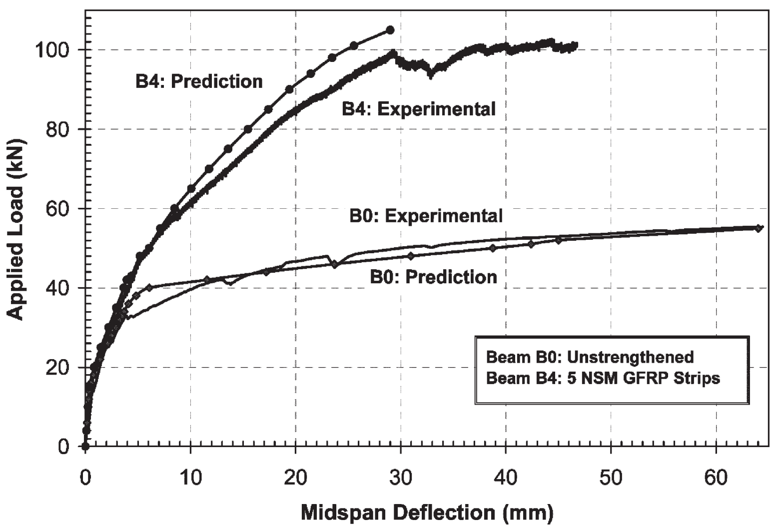

Figure 8 (d) - Load-Midspan Deflection Curves for Beams B0 and B4

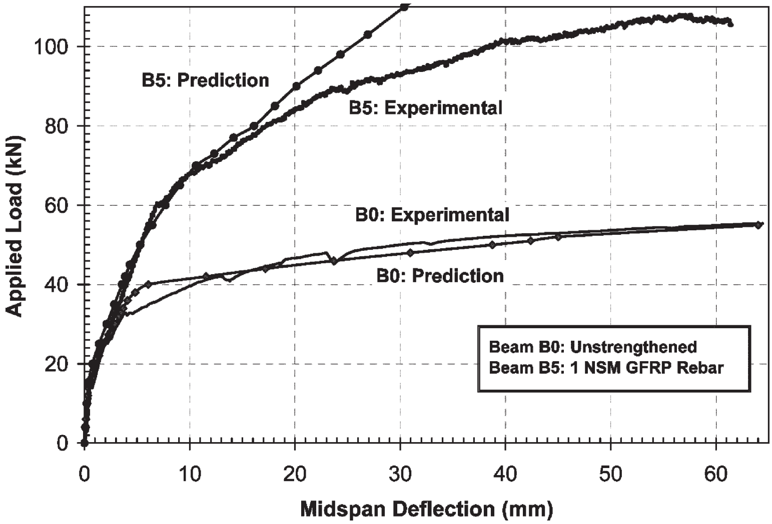

Figure 8 (e) - Load-Midspan Deflection Curves for Beams B0 and B5

Figure 8 - Comparison between Predicted and Experimental Load-Midspan Deflection of the Beams Strengthened with various NSM FRP Reinforcements

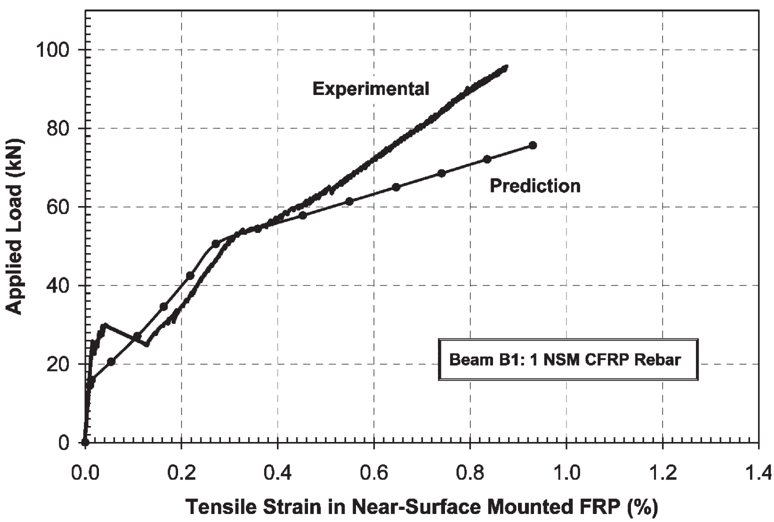

Figure 9 (a) - Load-FRP Tensile Strain Curves for Beam B1

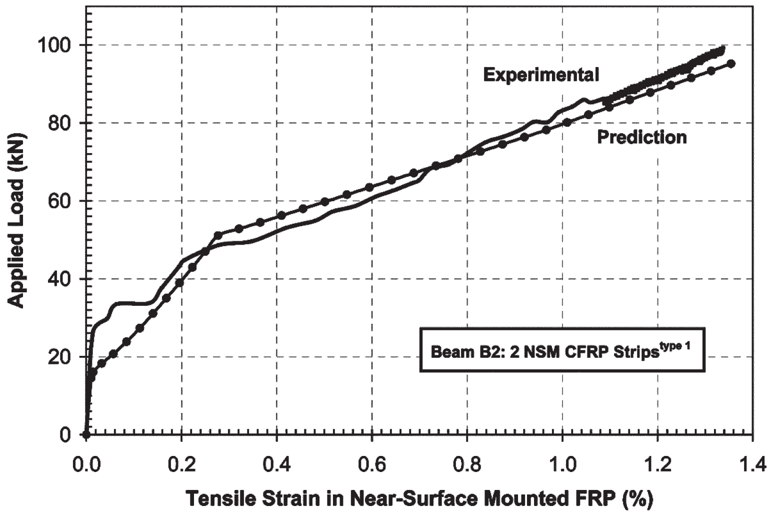

Figure 9 (b) - Load-FRP Tensile Strain Curves for Beam B2

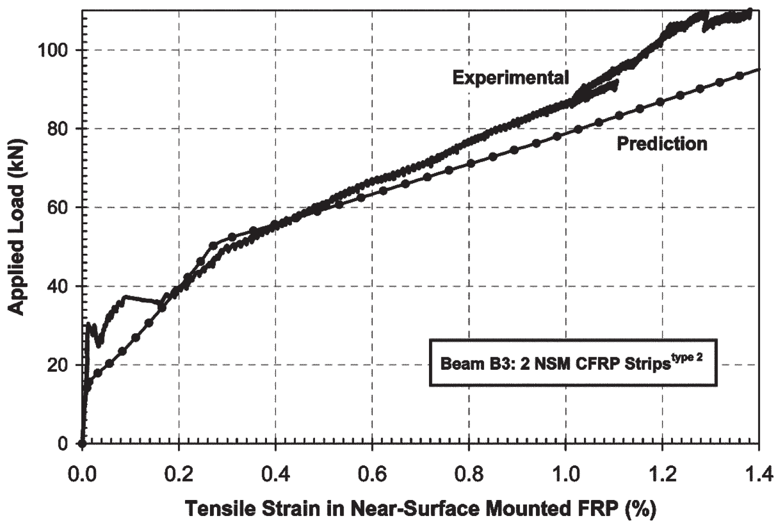

Figure 9 (c) - Load-FRP Tensile Strain Curves for Beam B3

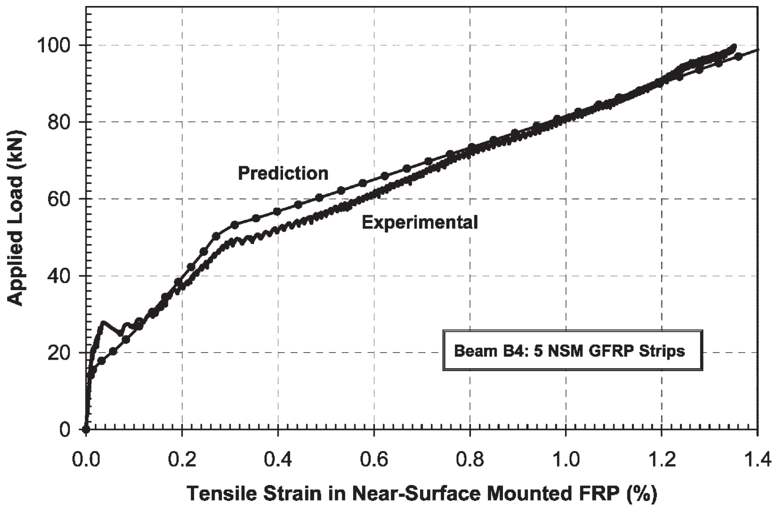

Figure 9 (d) - Load-FRP Tensile Strain Curves for Beam B4

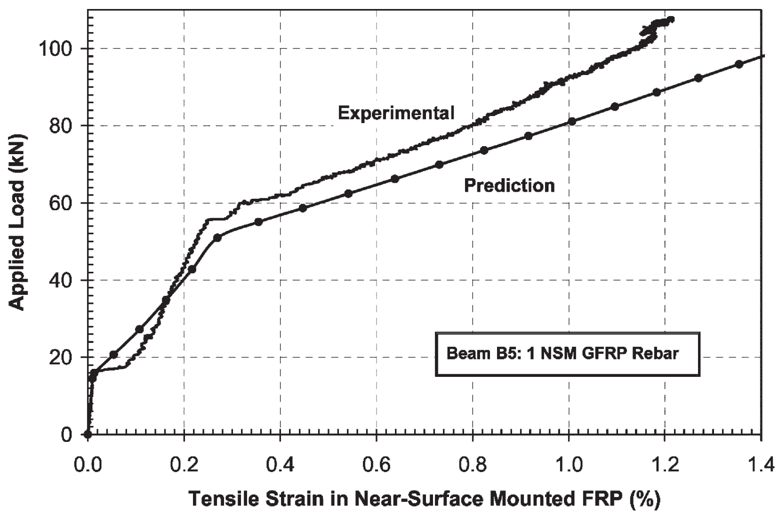

Figure 9 (e) - Load-FRP Tensile Strain Curves for Beam B5

Figure 9 - Comparison between Predicted and Experimental Load-Tensile Strain in the various NSM FRP Reinforcements