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Strengthening of Prestressed Concrete Beams Using Prestressed NSM CFRP Bars to Enhance Structural Performance

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ABSTRACT

In this study, prestressed concrete beams were strengthened using the NSM strengthening technique with CFRP bars which were prestressed using a pretensioning method. Seven prestressed beams were tested under monotonic four-point loading, with one unstrengthened control beam, one beam strengthened with a non-prestressed NSM CFRP bar and five beams strengthened with NSM CFRP bars prestressed to 30%, 40%, 50%, 60% and 70% of their nominal tensile strength. The effect of prestress level in the NSM CFRP bar on beam structural behavior and failure mode was investigated. The results indicated that prestressing the NSM CFRP bar increased first crack, yield and ultimate loads while decreasing deflection compared to unstrengthened and non-prestressed strengthened beams. The strengthened beams failed by CFRP bar rupture. The structural performance of the 70% prestressed strengthened beam showed the greatest enhancement, with first crack and ultimate loads increasing by 43% and 47%, respectively, over the control beam.

KEYWORDS: Prestressed concrete beams, Flexural strengthening, NSM CFRP bar, Prestressing level, Structural performance.

INTRODUCTION

Prestressed concrete beams are widely used in construction bridges and other long-span structures. To increase the lifespan and structural capacity of reinforced concrete structures, a number of strengthening techniques have developed, such as externally bonded reinforcement (EBR), near surface mounted (NSM) reinforcement and prestressed strengthening (Bsisu et al., 2012). Compared to EBR, NSM strengthening can provide superior protection from external mechanical and environmental damage, enhanced bond properties and stress sharing characteristics, as well as preservation of the dimensions and external faces of structures. Prestressed strengthening is used in combination with EBR and NSM to enhance performance by greater utilization of the tensile capacity of strengthening material. Practical systems for NSM prestressing and anchoring are being developed by researchers, such as De Lorenzis and Nanni (2002), Casadei et al., (2006), El- Hacha and Gaafar (2011) and de Albornoz et al., (2019), involving indirect and direct prestressing by tensioning against an independent external reaction frame or by tensioning against the strengthened beam itself.

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Prestressed NSM flexural strengthening provides an active strengthening system due to the upward cambering from prestressing which opposes loading and deflection. This increases load capacity at first crack, yield and ultimate load and improves serviceability by reducing deflection and crack widths, delaying new cracks and closing existing cracks (Casadei et al., 2006; Badawi and Soudki, 2009; El-Hacha and Gaafar, 2011; Rezazadeh et al., 2014; Wu et al., 2014; Obaydullah et al., 2016; Aslam et al., 2015; Lee et al., 2017). Other advantages of prestressed strengthening include: reduced internal reinforcement strains; compressive stresses that oppose dead and live loads and resist fatigue failure; increased yield load to a higher portion of ultimate capacity; increased fatigue strength, live load capacity and shear capacity; replacement of lost prestress force; and more efficient use of strengthening materials and concrete (De Lorenzis and Teng, 2007; El-Hacha and Soudki, 2013; Aslam et al., 2015).

Prestressed NSM CFRP to strengthen RC beams has been investigated by a number of researchers, with prestress levels varying from 5% to 60% of the tensile strength of the CFRP (El-Hacha and Gaafar, 2011; Nordin and Taljsten, 2006; Peng et al., 2014; Darain et al., 2015; Rezazadeh et al., 2014; Hong and Park, 2016; Jumaat et al., 2006). These studies have found that prestressed NSM CFRP strengthening enhances the overall flexural behavior of RC beams at both service and ultimate loads, compared to non-prestressed strengthened beams, with increased load capacity, especially at first crack and yield, reduced crack widths, improved crack distribution, reduced deflection and failure mostly occurring due to CFRP rupture after steel yielding. Thus, prestressed NSM CFRP strengthening improves the durability and serviceability of strengthened beams, which are further improved by increasing the prestress level. Increasing the prestress level also delays concrete cover separation and improves the composite behavior of the strengthened beams (Hong and Park, 2016). However, it was found that ductility is reduced, as a large part of the possible strain in the CFRP is used during prestressing, resulting in failure at smaller deflections.

Fewer studies have been conducted on the strengthening of prestressed concrete beams (compared to RC beams) using prestressed NSM strengthening. Casadei et al. (2006) conducted a pilot research on pre-damaged prestressed concrete I-girders to investigate the efficiency of prestressed NSM CFRP strengthening in restoring flexural strength and service performance. The CFRP bars were prestressed to around 33% of their ultimate strength, which was calculated to restore the original level of prestress in the beam. The tests found that the prestressed NSM CFRP-strengthened girder performed in a more ductile manner than EBR CFRP-strengthened beam, with improved performance in terms of symmetric behavior at both service and ultimate loads, thus restoring the functionality of the prestressed girder.

Prestressed concrete, although similar to conventional reinforced concrete, does not structurally perform in exactly the same manner. The prestress force in prestressed concrete beams allows them to reach a far higher level of structural performance. Strengthening prestressed concrete beams requires consideration of the internal prestress forces effects on bonding between prestressed concrete and strengthening reinforcement, loss of prestress force, restoration of prestress losses, and effect on stresses and strains in concrete and internal reinforcement. The addition of secondary prestress to prestressed beams in the form of prestressed strengthening can significantly improve performance, but it increases the urgency of understanding these various factors, in order to improve structural performance without compromising structural integrity and safety. As there are very few studies on prestressed strengthening of prestressed concrete, this study can be considered a significant contribution to this field.

This paper presents a study on the strengthening of prestressed concrete beams with prestressed NSM CFRP bars. The aim of this paper is to show that serviceability and ultimate performance of prestressed concrete beams are improved by strengthening with prestressed NSM CFRP in comparison to non-prestressed strengthening. The effect of varying the level of prestress force in the NSM CFRP bar was also investigated.

EXPERIMENTAL PROGRAM

Test Matrix

Seven prestressed concrete beams were tested with one unstrengthened control beam, one beam strengthened with a non-prestressed NSM CFRP bar and five beams strengthened with NSM CFRP bars prestressed to 30%, 40%, 50%, 60% and 70% of the maximum tensile strength of the CFRP. The test configurations are shown in Table 1.

Table 1. Test matrix

Specimen ID	Strengthening materials		Prestress level	Bond length (mm)
	Type	Diameter (mm)		
UB	unstrengthened beam		-	-
NSM-C-0%F	CFRP bar	10	0%	2900
NSM-C-30%F	CFRP bar	10	30%	2900
NSM-C-40%F	CFRP bar	10	40%	2900
NSM-C-50%F	CFRP bar	10	50%	2900
NSM-C-60%F	CFRP bar	10	60%	2900
NSM-C-70%F	CFRP bar	10	70%	2900

Material Properties

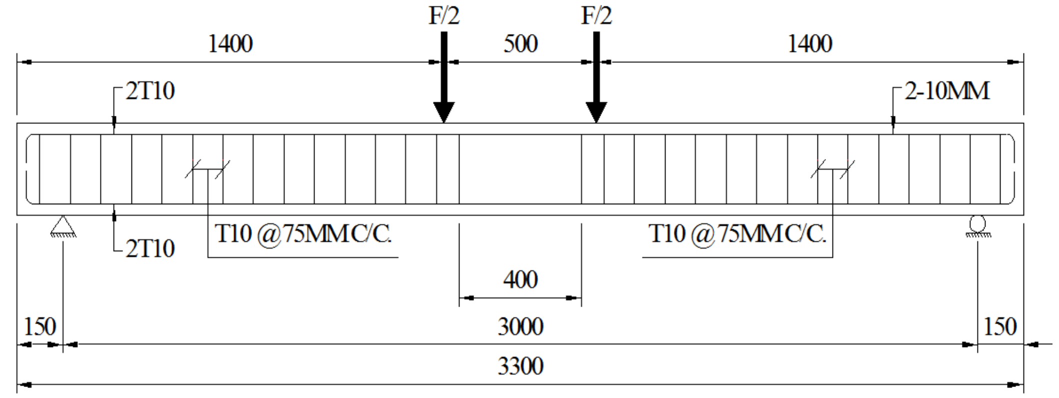
High-strength concrete was used to cast the beams. Ordinary Portland cement was used with crushed granite as coarse aggregate (maximum size 20 mm) and natural sand as fine aggregate. The water to cement ratio was 0.36. The 28-day compressive strength of the concrete was 50.1 MPa and the flexural strength was 5.5 MPa, based on concrete cube and prism tests in accordance with BS-EN-12390-3 (2009a) and BS-EN-12390-5 (2009b). The material properties are shown in Table 2.

Test Specimens

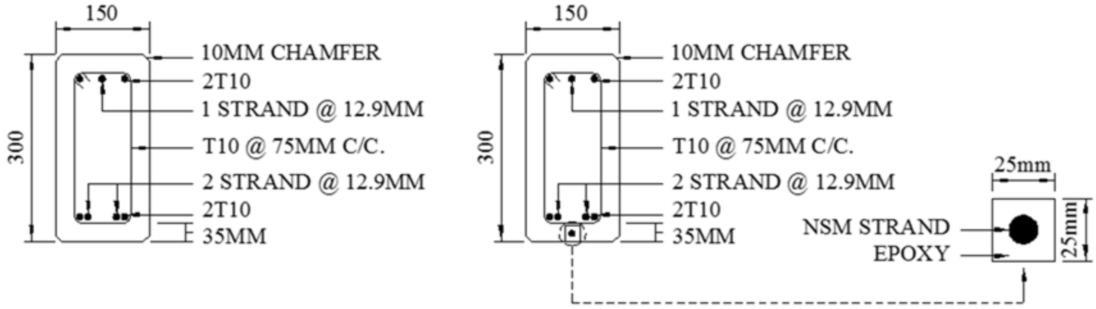
The prestressed beams were cast in a single pretensioning casting bed in one casting using the Hoyer long-line pretensioning system. The beams were designed for HB45 bridge loading, equivalent to 112.5kN wheel load (BD37-01). Three 12.9 mm diameter seven-wire prestressing strands with 75% prestress were used as internal reinforcement. The dimensions and rebar arrangement are shown in Figure (1). Cambering was 0.3-0.4mm after prestress transfer. The beams were cured for 28 days before strengthening.

Table 2. Material properties

Material	Property	Value
Concrete	Compressive strength	50.1 MPa
	Flexural strength	5.5 MPa
Steel rebar	Yield strength	500 MPa
	Modulus of elasticity	200 GPa
Prestressing strands	Tensile strength	1860 MPa
	Modulus of elasticity	195 GPa
CFRP	Tensile strength	1760 MPa
	Modulus of elasticity	135 GPa
Epoxy	Compressive strength	95 MPa
	Modulus of elasticity	11.2 GPa



(a) Longtitudnal cross-section



(b) Cross-section of unstrengthened beam **(c) Cross-section of strengthened beam**

Figure (1): Specimen details

Strengthening Procedure

For NSM strengthening, a groove, 25 mm by 25 mm (2.5 times the diameter of the NSM CFRP bar), was cut along the soffit of the beam and a CFRP bar, 10 mm in diameter, was used as NSM reinforcement. The bar size and groove dimensions were selected to ensure adequate concrete cover and clear cover, as well as sufficient epoxy for proper bonding, to prevent premature debonding failure (El-Hacha and Gaafar, 2011; Badawi and Soudki, 2009). A special prestressing setup, Figure (2), was used to apply and safely release prestressing force in the CFRP bars. The prepared beam with NSM groove was placed in the frame of the prestressing setup in inverted position. The CFRP bar was then anchored to the steel frame above the groove and prestressed with the hydraulic jack to the required level of prestress (30% to 70%). A digital pressure gauge was used to measure the prestress force. Clamps were then tightened to lock the prestressing system and prevent loss of prestressing force from the bar. The NSM groove was then half-filled with epoxy and the beam was raised slightly in the frame to lightly press the prestressed CFRP bar into the epoxy and then more epoxy was used to fill the groove completely. A minimum 10-mm clear cover from the soffit of the beam was maintained for all specimens. After curing the epoxy for six days, the prestressing force was gradually released to the beam by loosening the clamps and hydraulic jack. The specimens were allowed to cure for one more day before testing. The strengthening procedure used was possible in the laboratory, but is not applicable for usage on site, as the beams were inverted during strengthening. The beams were inverted for ease of access to the beam soffit, to facilitate strengthening and save time. For site application, a proper anchoring system needs to be developed.

Instrumentation and Test Setup

The beam specimens were simply supported and tested under monotonic four-point loading until failure using an Instron Universal testing machine, as shown in Figure (3). During testing, loading was slowly increased, firstly by controlling load (5 kN/ min) until near the calculated approximate yield load and then by displacement control (1.5 mm/min) until complete failure. Deflection was measured at midspan using a 100-mm Linear Variable Differential Transducer (LVDT) until near failure after which a conventional ruler was used to avoid damaging the LVDT. The data from the load-cell and LVDT was recorded using a portable data logger at a time interval of one second. Crack widths were measured using a digital microscope with an adjustable lens.

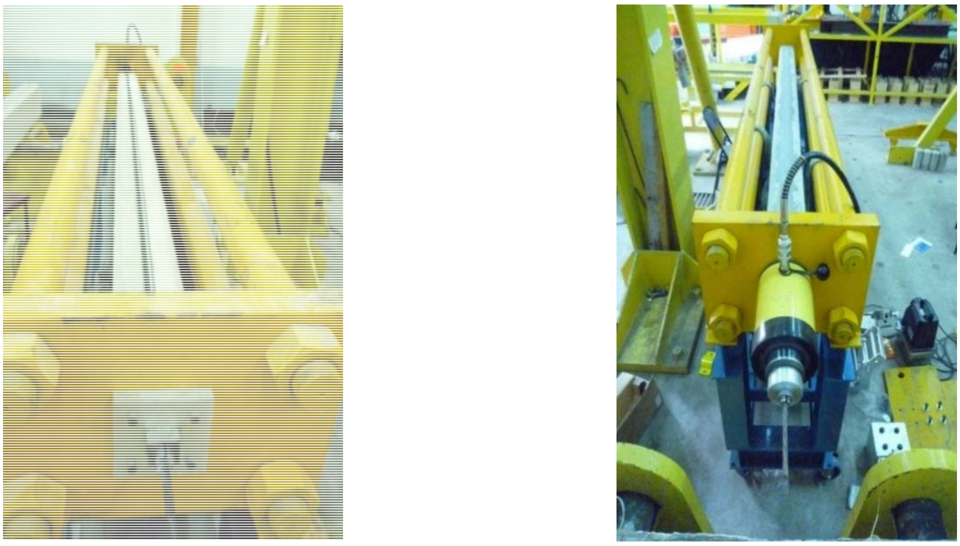

(a) During prestressing (dead end anchor) (b) After prestressing (live end hydraulic jack)

Figure (2): Prestressing system


Figure (3): Instrumentation and experimental setup

RESULTS AND DISCUSSION

Load Carrying Capacity

The exact load capacity values of the beams are presented in Table 3. First crack load increased remarkably in the beams strengthened with prestressed NSM CFRP bars. The first crack load of the 70% prestressed strengthened beam increased by 43% and 34% over the control beam and the non-prestressed strengthened beam. The SLS range is calculated as the load range from first crack load to the load corresponding to the point of deflection that is equal to the span/480 (Obaydullah et al., 2016), as provided in ACI 318-11. The SLS deflection for the beams was 6.25 mm and the corresponding SLS load notably improved in the prestressed NSM CFRP-strengthened beams. The SLS load of the 70% prestressed strengthened beam increased by 34% and 30% over the control beam and the non-prestressed strengthened beam. The yield load of the prestressed strengthened beams increased very significantly. Increasing the prestress force in the NSM CFRP caused the yield load to move closer to the ultimate load, improving serviceability and durability (Obaydullah et al., 2016; El-Hacha and Gaafar, 2011). The yield load of the 70% prestressed strengthened beam increased by 35% and 31% over the control beam and the non-prestressed strengthened beam. The ultimate load increased significantly with prestressed NSM CFRP strengthening with the 70% strengthened beam increasing by 47% and 12% over the control beam and the non-prestressed strengthened beam. The increase in ultimate load over the non-prestressed strengthened beam was less significant than the increases seen in yield and first-crack loads (Nordin and Taljsten, 2006; Peng et al., 2014).

Table 3. Experimental load and deflection results

Beam specimen	**First crack (P_{cr})**		**SLS load (kN)**	**Yield (P_y)**		**Ultimate (P_{ult})**	
	Load (kN)	**Deflection (mm)**		**Load (kN)**	**Deflection (mm)**	**Load (kN)**	**Deflection (mm)**
UB	63	3.1	83	110	19.8	127	45.6
NSM-C-0%F	67 (6%)	3.4	86 (3%)	113 (3%)	11.7	166 (31%)	40.1
NSM-C-30%F	77 (23%)	3.6	95 (14%)	122 (11%)	11.6	170 (34%)	38.6
NSM-C-40%F	79 (26%)	3.6	98 (17%)	124 (13%)	11.5	174 (37%)	38.1
NSM-C-50%F	82 (30%)	3.5	101 (22%)	133 (20%)	11.5	177 (40%)	37.1
NSM-C-60%F	86 (37%)	3.4	106 (28%)	140 (27%)	11.6	180 (42%)	36.5
NSM-C-70%F	90 (43%)	3.4	111 (34%)	149 (35%)	11.7	186 (47%)	35.1

Note: Values in parentheses represent percentage increase over control beam.

Failure Mode

The control beam failed typically by concrete crushing at the top fiber of the beam in the compression zone after yielding of the tension reinforcement. All the strengthened beams failed by rupture of the CFRP bar, after yielding of the tension reinforcement, in combination with concrete crushing, Figure (4). Concrete crushing began before CFRP bar rupture, but finished after FRP bar ruptured. When the CFRP bar ruptured, a loud sound was heard and spalling of part of the epoxy cover at the rupture location was observed. No debonding problems were observed during testing of the beams. The behavior of the beams at failure indicates that the beams performed in full composite action until failure. Flexural failure by CFRP rupture indicates full utilization of the CFRP material (Badawi and Soudki, 2009; Haddad and Almomani, 2019).

(a) control beam (UB)

(b) NSM-C-0%F

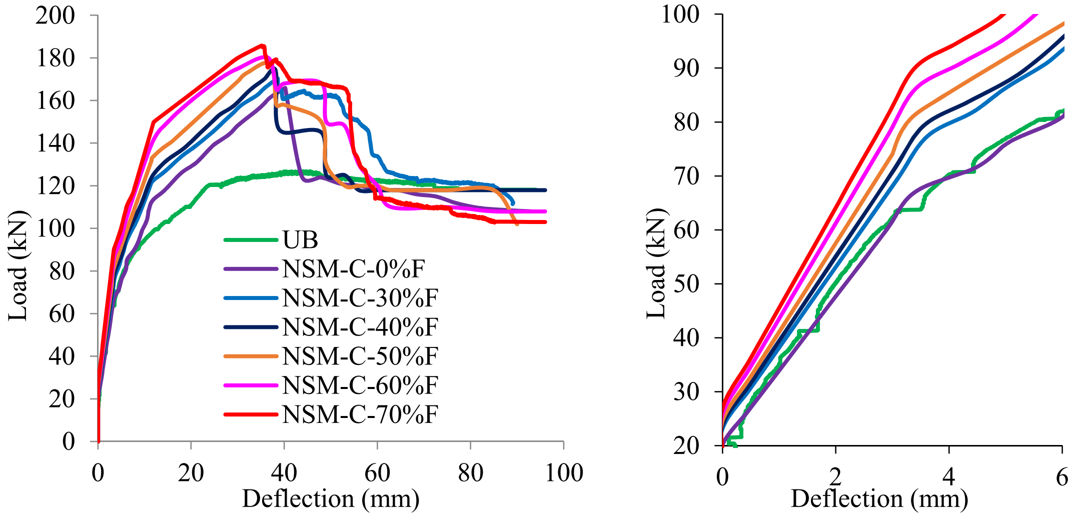
(c) NSM-C-60%F

(d) NSM-C-70%F

Figure (4): Failure modes

Load-Deflection Behavior

The load-deflection curves of the beams are presented in Figure (5) and specific values are given in Table 3. The strengthened beams displayed the typical tri-linear response of CFRP-strengthened beams. Higher levels of prestress in the NSM CFRP bar resulted in steeper load deflection curves, indicating increased stiffness and flexural strength, as well as reduced deflection, at similar load levels. From load initiation to first crack, the load-deflection curves were steep and linear with minimal deflection, as the beams were at full functionality with no loss of stiffness, Figure (5) (b). The deflection at first crack was 3.1 mm for the control beam and around 3.5 mm for the strengthened beams. After first crack, the steepness of the load-deflection curves was slightly reduced as the initial beam stiffness was lost and deflection increased. The deflection at yield for the control beam was 19.8 mm and for the strengthened beams around 11.5 mm. Deflection at first crack and yield did not significantly increase in the prestressed strengthened beams, despite significant increases in first crack and yield loads. After yield, the steepness of the load-deflection curves was again reduced, as cracks widened, beam stiffness was reduced and deflection increased. Ultimately, the prestressed strengthened beams displayed significantly reduced deflections with simultaneously higher ultimate loads with the 70% beam showing 23% and 13% less deflection than the control beam and the non-prestressed strengthened beam. After failure at ultimate load, the beams could take no further loading and deflection increased greatly. The control beam displayed the typical ductile behavior after failure of reinforced beams with increasing deflection at load levels slightly lower than the ultimate load. The non-prestressed strengthened beam displayed a single sharp drop in load capacity, with little deflection, back to the level of the control beam. The prestressed strengthened beams displayed greater deflection in the fall from ultimate back to the level of the control beam, as the prestressed CFRP ruptured in a more progressive manner in stages where load capacity fell in several smaller drops back to the level of the control beam. After the load capacity of the strengthened beams fell to the level of the control beam, beam behavior became similar to that of the control beam, as behavior is then controlled by the main tensile steel reinforcement.



(a) Load-deflection curves for all loads **(b) Zoom of curves at low loads**

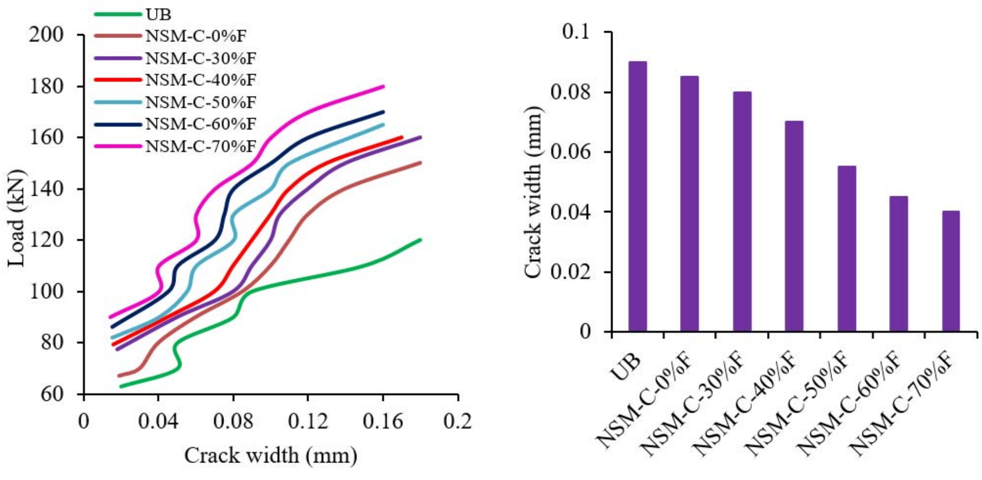
Figure (5): Load-deflection

Cracking Behavior

The beams displayed typical flexural crack patterns, where the cracks were more developed at midspan and less towards the ends of the beam specimens, Figure (4). The strengthened beams displayed full composite behavior with no longitudinal cracks at the soffit of the beams between the epoxy and concrete or at the level of the bottom steel. The cracking behavior of all the strengthened beams improved in terms of first crack load, crack width, crack number and crack spacing, compared to the control beam.

First-crack load improved considerably in the prestressed strengthened beams by about 23% to 43% over the control beam, and 15% to 34% over the non-prestressed strengthened beam, Table 2.

For all the beams, the first crack appeared around midspan between the two load points and typically developed into the main crack with a relatively larger width than the other cracks. The width of this crack was measured for each specimen throughout testing. The crack width at different load levels can be seen in Figure (6) (a). Prestressed NSM CFRP strengthening significantly reduced crack width compared to the control beam and non-prestressed strengthened beam and for any given load level, such as 100 kN as in Figure (6) (b), crack width reduced significantly with increasing prestress force. The 70% prestressed strengthened beam had a 56% and 53% decrease in crack width compared to the control beam and non-prestressed strengthened beam.



(a) Load *vs.* crack width **(b) Crack width at 100 kN**

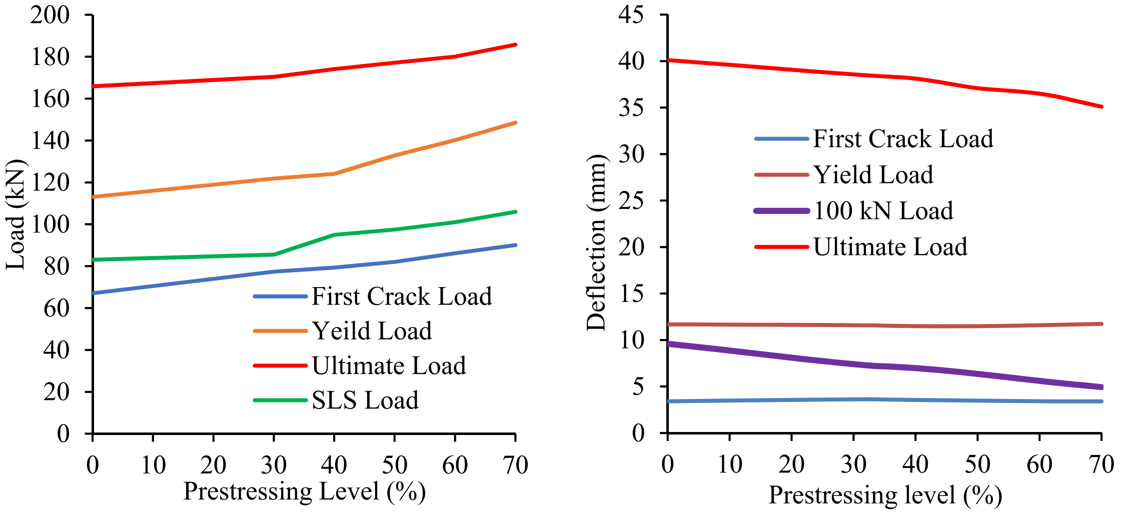
Figure (6): Crack width

The strengthened beams also displayed more flexural cracks with closer spacing, smaller crack widths and more uniform distribution, compared to the control beam. The control beam had 15 cracks, while the strengthened beams had around 25 to 30 cracks each. The higher number of cracks produced closer spacing and smaller crack widths (Choi et al., 2010; Rezazadeh et al., 2014).

Strengthening with prestressed NSM CFRP significantly improved the cracking behavior of the beams, with higher first-crack loads, better crack distribution and reduced crack widths. Increasing the prestress force in the strengthening bar further enhanced these beneficial effects, as the additional prestress induced more compressive forces in the beams, which balanced internal bending forces from applied loads. This compressive action of prestressed strengthening can be useful in field practice as an additional method to reduce crack widths or even close cracks.

Effect of Prestressing the NSM CFRP Bar

Prestressing the strengthening NSM CFRP bar significantly influenced and enhanced the flexural behavior of the beams. Overall, the load bearing capacity of the beams increased significantly at all crucial load stages, as can be seen from Figure (7) (a). Higher levels of prestress corresponded to higher loads, with the 70% prestressed strengthened beam showing the greatest increase in load capacity at all stages. The load capacity at the service stage (from first crack to yield) was especially enhanced by prestressing the NSM CFRP bar. The deflection of the strengthened beams decreased with increasing prestressing level at any given load level. For instance, at an arbitrarily chosen load level of 100 kN, the deflection of the prestressed strengthened beams dropped from 10 mm (NSM-C-0%F) to 5 mm (NSM-C-70%F), as shown in Figure (7) (b). The deflection at first crack and yield was similar for all the strengthened specimens despite the large increases in load for the prestressed strengthened beams at these two crucial stages. This indicates that the prestressed strengthening was largely able to control deflection during the service stage. At the ultimate stage, deflection decreased slightly with increasing level of prestressed strengthening despite increased ultimate loads, due to the greater stiffness of the prestressed strengthened beams. Deflection dropped at ultimate load from 40 mm (NSM-C-0%F) to 35 mm (NSM-C-70%F), a drop of 12.5%. Cracking behavior in terms of crack distribution and crack widths also improved with prestressed strengthening. The failure mode of the beams was not affected by prestressing the strengthening bar. All the prestressed beams failed flexurally by CFRP rupture and concrete crushing, which is the same mode as for the control and non-prestressed strengthened beams. This indicates that prestressing the strengthening material even to high levels of prestress did not compromise the full composite action of the strengthened beams.



(a) Load *vs.* prestressing level **(b) Deflection *vs.* prestressing level**

Figure (7): Load, deflection and prestressing level

CONCLUSIONS

(1) The use of prestressed NSM CFRP bars as flexural strengthening for prestressed concrete beams was proven to be effective.

(2) The addition of prestressed strengthening to the prestressed beams did not cause any adverse effects. No cracking was observed during the release of the prestress force from the NSM CFRP.

(3) Using a maximum of 70% prestress force in the NSM CFRP was the most effective prestress level, without causing any negative effect to the prestressed beams.

(4) Increasing the level of prestressing force from 0% to 70% in the NSM CFRP bars enhanced the service and ultimate loads from 3% to 34% and from 31% to 47%, respectively, over the control beam.

(5) First-crack load and yield load also improved by 6% to 43% and by 3% to 35%, respectively, over the control beam and crack width and deflection were significantly reduced.

(6) All the strengthened beams failed by CFRP rupture with concrete crushing. No debonding was observed, indicating full composite behavior of the beams.

(7) Overall, this study has found that strengthening prestressed beams with prestressed NSM CFRP bars is an effective strengthening technique capable of fulfilling the serviceability requirements of reinforced concrete structures. As the prestressing technique used in this study is feasible only in the laboratory, a practical prestressing and anchorage technique for on-site application needs to be developed. Further studies on the short-term and long-term loss of prestress force also need to be done. Thus, prestressed strengthening with NSM CFRP bars could be adapted for real-life application with some further development.

REFERENCES

Aslam, M., Shafigh, P., Jumaat, M. Z., and Shah, S. N. R. (2015). “Strengthening of RC beams using prestressed fiber-reinforced polymers: A review.” Construction and Building Materials, 82, 235-256.

Badawi, M., and Soudki, K. (2009). “Flexural strengthening of RC beams with prestressed NSM CFRP rods: Experimental and analytical investigation.” Construction and Building Materials, 23 (10), 3292-3300.

Bsisu, K. A. D., Hunaiti, Y., and Younes, R. (2012). “Flexural ductility behavior of strengthened reinforced concrete beams using steel and CFRP plates.” Jordan Journal of Civil Engineering, 6 (1), 1-9.

Casadei, P., Galati, N., Boschetto, G., Tan, K. Y., Nanni, A., and Galecki, G. (2006). “Strengthening of impacted prestressed concrete bridge I-girder using prestressed near-surface mounted C-FRP bars.” Proceedings of the 2nd International Congress, June, 5-8.

Choi, H. T., West, J. S., and Soudki, K. A. (2011). “Effect of partial unbonding on prestressed near-surface-mounted CFRP-strengthened concrete T-beams.” Journal of Composites for Construction, 15 (1), 93-102.

Darain, K. M., Jumaat, M. Z., Hossain, M. A., Hosen, M. A., Obaydullah, M., Huda, M. N., and Hossain, I. (2015). “Automated serviceability prediction of NSM-strengthened structure using a fuzzy logic expert system.” Expert Systems with Applications, 42(1), 376-389.

de Albornoz, V. A. C., del Toro, E. M. G., Más-López, M. I., and Patiño, A. L. (2019). “Experimental study of a new strengthening technique of RC beams using prestressed NSM CFRP bars.” Sustainability, 11(5), 1-16.

De Lorenzis, L., and Nanni, A. (2002). “Bond between near-surface mounted fiber-reinforced polymer rods and concrete in structural strengthening.” Structural Journal, 99 (2), 123-132.

De Lorenzis, L., and Teng, J. G. (2007). “Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures.” Composites-Part B: Engineering, 38 (2), 119-143.

El-Hacha, R., and Gaafar, M. (2011). “Flexural strengthening of reinforced concrete beams using prestressed, near-surface mounted CFRP bars.” PCI Journal, 56(4).

El-Hacha, R., and Soudki, K. (2013). "Prestressed near-surface mounted fibre-reinforced polymer reinforcement for concrete structures: A review." Canadian Journal of Civil Engineering, 40 (11), 1127-1139.

Haddad, R.H., and Almomani, O.A. (2019). "Flexural performance and failure modes of NSM CFRP-strengthened concrete beams: A parametric study." International Journal of Civil Engineering, 17 (7), 935-948.

Hong, S., and Park, S. K. (2016). "Effect of prestress and transverse grooves on reinforced concrete beams prestressed with near-surface-mounted carbon fiber-reinforced polymer plates." Composites-Part B: Engineering, 91, 640-650.

Huda, M. N., Jumaat, M. Z., Islam, A. B. M., Obaydullah, M., and Hosen, M. A. (2017). "Palm oil industry's byproducts as coarse aggregate in structural lightweight concrete." Computers and Concrete, 19 (5), 515-526.

Jumaat, M. Z., Kabir, M. H., and Obaydullah, M. (2006). "A review of the repair of reinforced concrete beams." Journal of Applied Science Research, 2(6), 317-326.

Lee, H., Jung, W. T., and Chung, W. (2017). "Post-tension near-surface-mounted strengthening systems of full-scale PSC girders." Construction and Building Materials, 151, 71-82.

Nordin, H., and Täljsten, B. (2006). "Concrete beams strengthened with prestressed near-surface-mounted CFRP." Journal of Composites for Construction, 10 (1), 60-68.

Obaydullah, M., Jumaat, M. Z., Alengaram, U. J., Darain, K. M., Huda, M. N., and Hosen, M. A. (2016). "Prestressing of NSM steel strands to enhance the structural performance of prestressed concrete beams." Construction and Building Materials, 129, 289-301.

Peng, H., Zhang, J., Cai, C. S., and Liu, Y. (2014). "An experimental study on reinforced concrete beams strengthened with prestressed near-surface-mounted CFRP strips." Engineering Structures, 79, 222-233.

Rezazadeh, M., Costa, I., and Barros, J.J.C.S. (2014). "Influence of prestress level on NSM CFRP laminates for the flexural strengthening of RC beams." Composite Structures, 116, 489-500.

Standard, A. A. (2011). "Building code requirements for structural concrete (ACI 318-11)." American Concrete Institute.

Wu, G., Dong, Z. Q., Wu, Z. S., and Zhang, L. W. (2014). "Performance and parametric analysis of flexural strengthening for RC beams with NSM-CFRP bars." Journal of Composites for Construction, 18 (4), 04013051.