Flexural strengthening of reinforced concrete beams using prestressed, near-surface-mounted CFRP bars

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The use of near-surface-mounted (NSM) carbon-fiber-reinforced polymer (CFRP) reinforcement is emerging as a promising strengthening technique and a valid alternative to CFRP reinforcement externally bonded to the tensile face of a concrete member.[1] The NSM technique consists of placing the CFRP reinforcing bars into grooves cut into the cover in the tension region of the concrete member and filled with high-strength epoxy adhesive. The flexural behavior of concrete beams strengthened with nonprestressed NSM CFRP reinforcing bars and strips has been investigated extensively under static and fatigue loading.[1–12] The bond mechanisms between the reinforcement and the epoxy or concrete was investigated experimentally and analytically.[13–18] Although NSM CFRP can increase the ultimate strength, NSM CFRP reinforcement does not significantly change the behavior of the member under service loads. Thus, to improve the efficiency of the NSM strengthening technique, the CFRP reinforcement can be prestressed. This technique combines the advantages of noncorrosive and lightweight CFRP reinforcement with the efficiency of external prestressing. The CFRP is used more efficiently because a greater portion of its tensile capacity is employed, and it contributes to the load-bearing capacity under both service and ultimate conditions. It closes cracks, delays the opening of new ones, and can restore prestress to a system that has suffered a loss of internal prestressing.

- Premature failure may occur in beams strengthened with nonprestressed, near-surface-mounted (NSM) fiber-reinforced polymer, leading to failure at loads below the designed capacity.
- This paper examines the effect of varying the prestressing levels in the carbon-fiber-reinforced polymer (CFRP) bars.
- Prestressing the embedded NSM CFRP reinforcement enhanced the overall performance of the beams by increasing the loads at cracking, yielding, and ultimate.

Several researchers have studied the flexural behavior of concrete beams strengthened with prestressed NSM CFRP and tested under quasistatic monotonic loading.[11,19–23] However, in those studies the beam was inverted and a groove was cut into the tension face and filled with epoxy. The CFRP bars were tensioned by jacking and reacting against an external steel frame independent of the beam before insertion into the groove. After curing, the CFRP reinforcement was cut at the ends and the forces were transferred from the steel frame to the beam. This method requires specialized equipment and is not practical for field application. The authors have developed an anchorage system for prestressing NSM CFRP bars by jacking and reacting against the concrete member itself.[24] This method is not limited by accessibility requirements because all components are easily handled and mounted directly on the member. The working area on the bridge can be easily accessed from above.

This paper presents the findings of an experimental investigation of the flexural behavior of large-scale reinforced concrete beams strengthened in flexure with NSM CFRP bars tensioned against the beam. The effect of varying the prestressing level from 0% to 60% of the ultimate strength of the CFRP on the overall flexural behavior of the beams was examined.

Experimental program

Test specimens and setup

Five reinforced concrete beams were constructed and tested to failure under quasistatic monotonic four-point loading. The load was applied using a 250 kN (56.2 kip) closed-loop controller testing machine operating using stroke-control mode at a constant loading rate of 1.0 mm/min (0.04 in./min) until yielding. The loading rate was then increased to 3 mm/min (0.12 in./min) until failure. The beams were 5.15 m (16.9 ft) long and 5.0 m (16.4 ft) long center to center between the supports with a typical rectangular cross section 200 mm (7.87 in.) wide and 400 mm (15.75 in.) deep. **Figure 1** shows the test setup, elevation, cross section, and reinforcement.

The bottom reinforcement consisted of three 15M (no. 5) deformed steel bars with a nominal diameter of 16 mm (0.63 in.) and a total area of 600 mm^2 (0.93 in.^{2}) at an effective depth of 343 mm (13.5 in.) from the top. The longitudinal top reinforcement consisted of two stirrup hangers of 10M (no. 3) deformed steel bars with a nominal diameter of 11.3 mm (0.445 in.) and a total area of 200 mm^2 (0.31 in.^{2}) at an effective depth of 35 mm (1.38 in.). The clear cover over the top and bottom reinforcement was 19 mm (0.75 in.) and 38 mm (1.5 in.), respectively. Double-legged 10M (no. 3) deformed steel stirrups were uniformly spaced at 200 mm (7.87 in.) center to center along the shear span and at 300 mm (11.81 in.) center to center in the constant-moment region. For the design, the specified yield strength of the steel was taken as 400 MPa (58 ksi). The yield strength and modulus of elasticity were 500 MPa (72.5 ksi) and 200 GPa (29,000 ksi), respectively, for the 10M (no. 3) reinforcing bars and 475 MPa (68.9 ksi) and 200 GPa (29,000 ksi) for the 15M (no. 5) reinforcing bars based on test results in accordance with ASTM A370-02.[25] The concrete had a specified 28-day compressive strength of 40 MPa (5.8 ksi). The compressive strengths at the time of testing were determined for each beam from tests on three 100 mm × 200 mm (3.94 in. × 7.87 in.) cylinders cured under the same conditions as the beams and tested in accordance with ASTM C 192/C 192M-00.[26]

The beams were designed according to the CSA 23.3-04[27] and ISIS M04-01[28] to avoid compression failure of the concrete before failure of the strengthening system and to prevent shear failure of the strengthened beams. The strengthened beams were designed to achieve a 30% increase in ultimate strength and to fail due to rupture of the NSM CFRP bars after yielding of the steel.

FRP materials

The CFRP bars had a nominal diameter of 9 mm (0.35 in.) and an area of 65.2 mm^2 (0.101 in.^{2}). Each beam was strengthened with one NSM CFRP bar. According to the manufacturer, the elastic modulus is 124 GPa (18,000 ksi) with an ultimate tensile stress of 2068 MPa (300 ksi) and ultimate strain of 0.017.[29] The CFRP bars were tested in uniaxial tension according to ACI 440.3R-04.[30] From the tests, the tensile strength and modulus of elasticity were 2167 MPa ± 46 MPa (314 ksi ± 6.7 ksi) and 130 GPa ± 2 GPa (18,855 ksi ± 290 ksi), respectively, at 0.01667 ± 0.00055 ultimate strain. This type of CFRP bar has a rough surface to enhance bond.

Epoxy adhesive was used to bond the CFRP bars inside the groove cut into the underside of the beam. For NSM strengthening, high viscosity helps to retain the epoxy inside the groove. According to the manufacturer's product guide specification, the tensile strength of the epoxy is 24.8 MPa (3.6 ksi) and the modulus of elasticity is 4482 MPa (650 ksi) after 7 days at 20 °C (68 °F), while the maximum elongation is 1%. The bond strength with concrete is 18.6 MPa (2.7 ksi) after two days of curing.

Instrumentation

All beam specimens were instrumented to measure the applied load, deflections, strain in the concrete through the depth of the beam, and strain in the CFRP bars and the longitudinal reinforcing steel. Deflections at midspan and under the point loads were measured using linear strain conversion devices (LSCs) and string potentiometers, respectively (**Fig. 2**). Strain distribution in the concrete at midspan over the depth of the beam was measured using

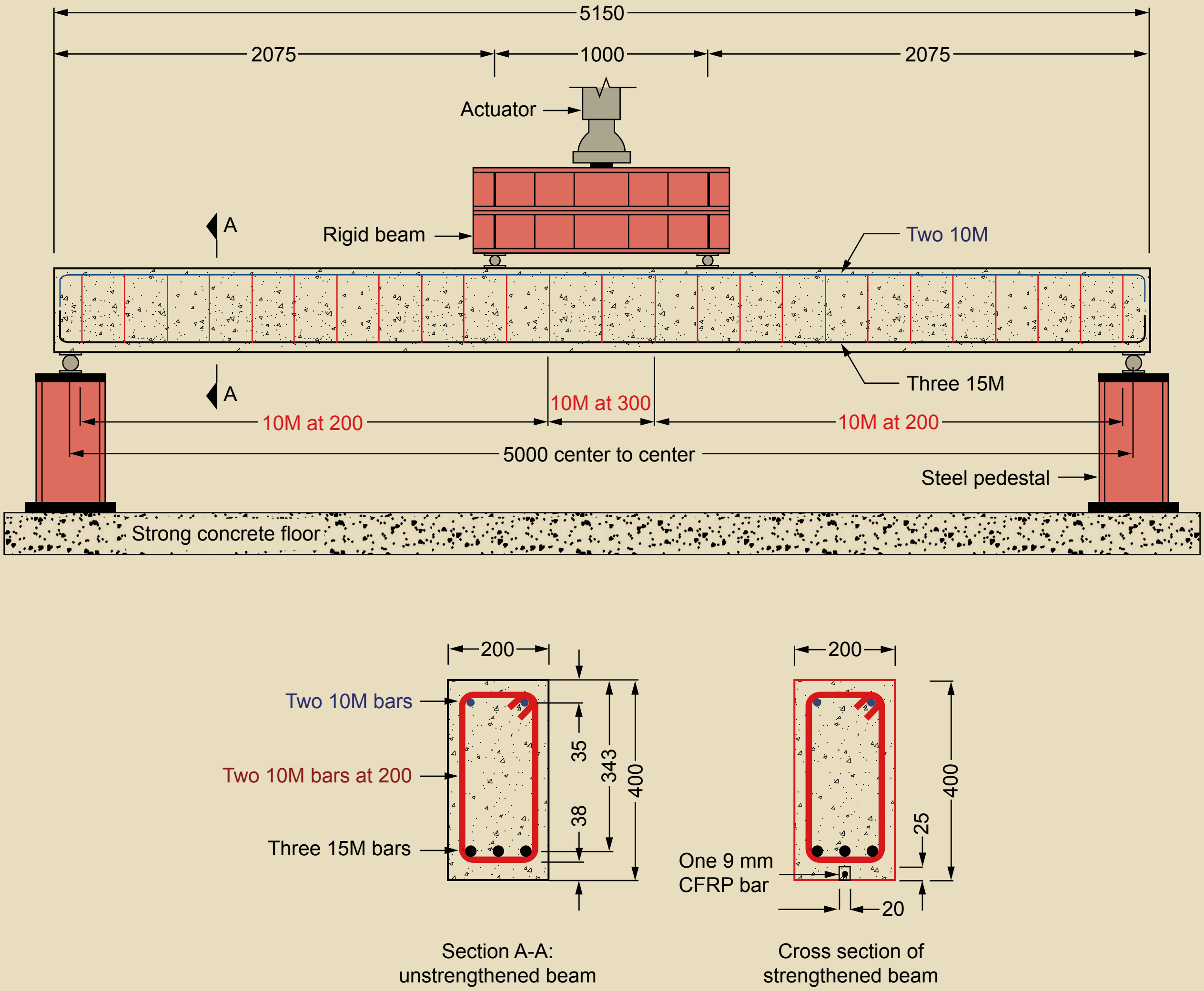


Figure 1. Test setup, elevation, cross-section, and reinforcement details. Note: All dimensions are in millimeters. CFRP = carbon-fiber-reinforced polymer. 1 mm = 0.0394 in.; 10M = no. 3; 15M = no. 5.

two LSCs mounted on the top fibers of the concrete and two LSCs mounted on each side of the beam at the level of the bottom reinforcement (Fig. 2). Electrical resistance strain gauges were installed at midspan on the longitudinal reinforcing steel and along the length of the CFRP bars (Fig. 2). All readings were recorded at one-second intervals up to failure by a data acquisition system.

Test matrix

Five beams were tested. One control beam was not strengthened, one beam was strengthened with nonprestressed NSM CFRP bars, and three beams were strengthened with NSM CFRP bars prestressed to 20%, 40%, or 60% of the ultimate tensile strength of the CFRP material as reported by the manufacturer. For each strengthened beam, one CFRP bar was used.

Strengthening procedure

Twenty-eight days after casting, a groove was cut into the concrete cover of each beam in the longitudinal direction on the tension side. The beams were inverted to facilitate cutting. The depth of the groove was 25 mm (0.98 in.), and the width was about 22 mm (0.87 in.). The grooves were cleaned with a water jet and dried with compressed air. The beams were left to dry at room temperature for at least seven days.

The CFRP bars were prestressed by pulling and reacting against the beam. Two steel anchors were bonded to the ends of the CFRP bars with epoxy, one at the fixed (dead) end of the beam and the other at the jacking end. Steel brackets were temporarily bolted to the jacking end of the beam. One bracket supported the hydraulic jack while the other transferred the force from the jack to the movable steel anchor. Once the system was prestressed to the

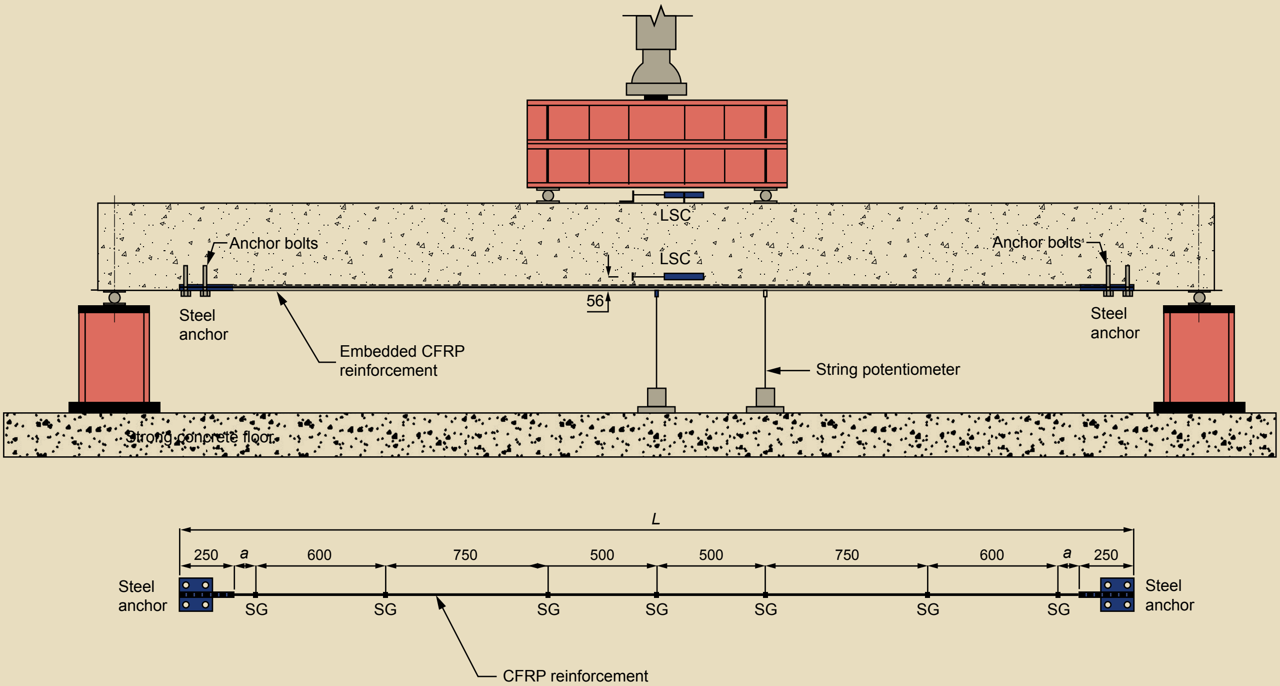


Figure 2. Instrumentation. Note: All dimensions are in millimeters. *a* = variable length depending on the elongation (90 mm, 82.5 mm, 75 mm, and 67.5 mm for beams B2-0%, B2-20%, B2-40%, and B2-60%, respectively); *L* = total length of carbon-fiber-reinforced polymer bar (4380 mm, 4365 mm, 4350 mm, and 4335 mm for beams B2-0%, B2-20%, B2-40%, and B2-60%, respectively); LSC = linear strain conversion; SG = strain gauge. 1 mm = 0.0394 in.

required force, the steel anchor at the jacking end was fixed to the concrete using anchor bolts and the temporary components were removed. **Figure 3** shows the components of the anchorage/prestressing system. It should be noted that the mechanical steel anchors at the ends of the NSM CFRP bars were embedded in the beams.

The CFRP bars were cut to the required length depending on the prestressing force to be induced (**Table 1**), and strain gauges were installed along the length of the CFRP reinforcing bars (Fig. 2). The CFRP bars were bonded to the steel anchors and left for seven days to cure. Epoxy was injected into the groove to about $^3/_4$ full. The anchors with the CFRP bar were lightly pressed into the groove and the groove was filled with additional epoxy. Excess epoxy was removed using a spatula. The CFRP bar was then prestressed to the required limit. The strengthened beams were left to cure at room temperature for seven days before testing to failure. The strains in the NSM CFRP bar were monitored during prestressing, at release, during the seven-day curing period, and throughout testing. More details can be found in Gaafar and El-Hacha[24] and Gaafar.[31]

Results and discussion

Figure 4 shows the load versus midspan deflection for the beams. The area under the curve was calculated to determine the amount of energy absorbed by the beams. The ductility index of the beams was calculated as the ratio of deflection at ultimate load to deflection at yielding of steel. For each beam, the strain distribution is illustrated across the height of the section at midspan (**Fig. 5**). The strains reported were the average values from the LSCs at the top concrete fibers and the strain gauges on the top and bottom steel reinforcement and the CFRP bars. **Figure 6** presents the strain profile along the length of the NSM CFRP bars. **Figure 7** shows the relationships among the load and the strain in concrete, bottom steel, and CFRP. Table 1 summarizes the prestressing data and test matrix. **Table 2** reports the experimental results.

Load-deflection behavior

For the control beam (B00), the load versus midspan deflection was typical of an underreinforced concrete beam (Fig. 4). The response was linear until crack initiation, then linear at a shallower slope until the steel yielded. At midspan, the concrete began to crush at an average strain of 0.00325, corresponding to a load of 83.2 kN (18.7 kip) and a deflection of 60.8 mm (2.39 in.). Finally, the compression zone crushed at an average strain of 0.00461, corresponding to an ultimate load of 83.8 kN (18.8 kip) and a deflection of 109.9 mm (4.33 in.).

Similarly, for the strengthened beams, the load versus midspan deflection relation was linear until crack initiation, then linear at a shallower slope until the tension steel yielded (Fig. 4). However, instead of the nearly ideal elas-

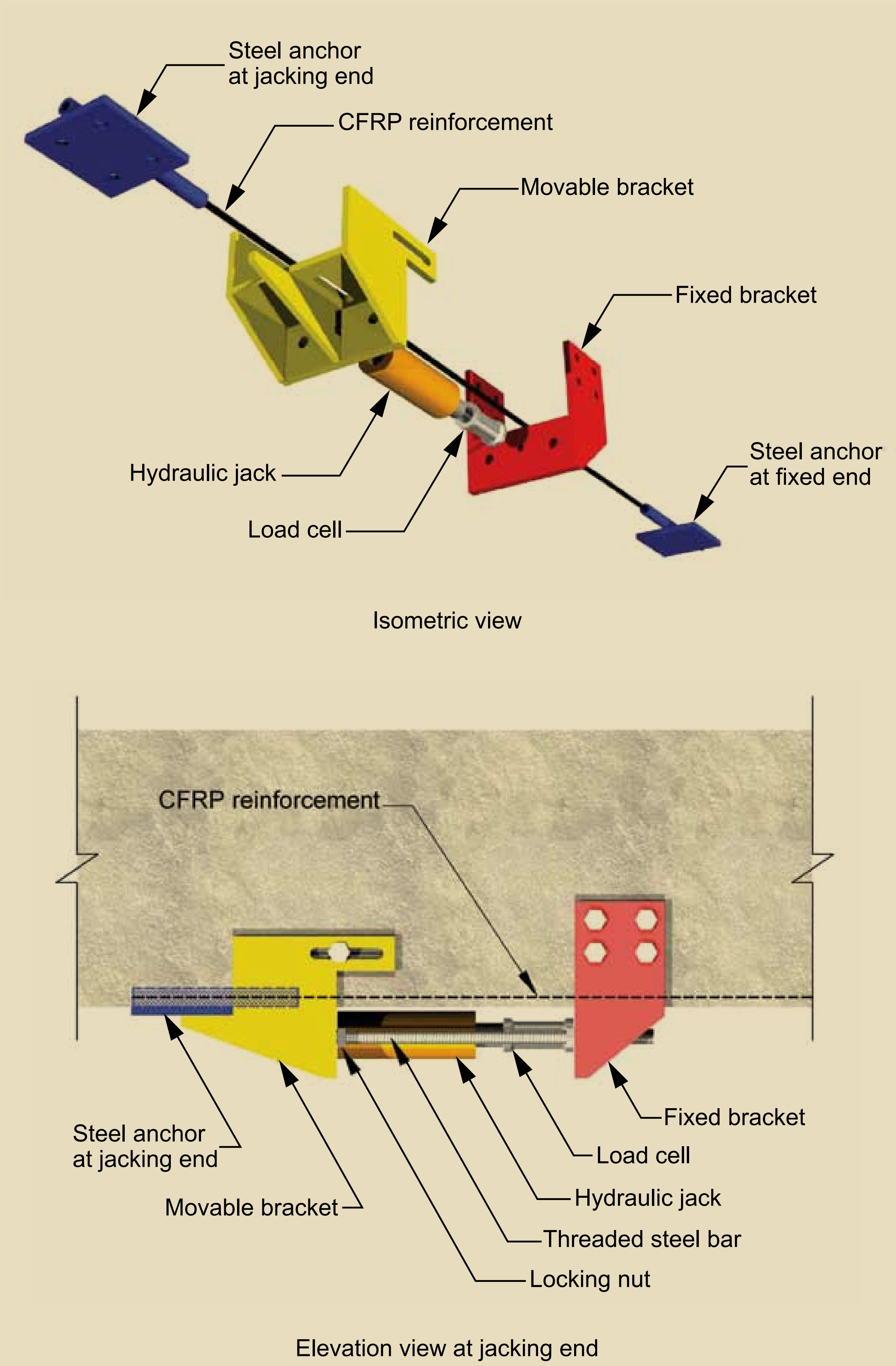


Figure 3. Components of prestressing system. Note: CFRP = carbon-fiber-reinforced polymer.

Table 1. Prestressing forces, strains, and stresses for beams

Beam identification	Target prestressing*		Induced prestressing before losses			Effective prestressing	
	Stress, MPa	Force, kN	Force,† kN	Stress, MPa	Percentage of $f_{CFRP,u}$‡	Strain	Percentage of $f_{CFRP,u}$‡
B00	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
B2-0%	0	0	0	0	0	0	0
B2-20%	413.6	26.9	29.3	449.4	20.74	0.00346	19.44
B2-40%	827.2	53.9	56.0	858.9	39.64	0.00621	37.25
B2-60%	1240.88	80.9	84.0	1288.3	59.45	0.00896	53.75

* Based on manufacturer data

† Based on readings from load cell mounted on the hydraulic jack

‡ Based on tension test data

Note: $f_{CFRP,u}$ = ultimate tensile strength of carbon-fiber-reinforced polymer bar; n.a. = not applicable. 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

tic-plastic response of the control beam, for the strengthened beams the load continued to increase until the CFRP reinforcement ruptured, after which the load dropped to that of the control beam.

Prestressing the embedded CFRP reinforcement enhanced the overall performance of the beams by increasing the loads at cracking, yielding, and ultimate. Serviceability was improved by reducing the deflections in the strengthened prestressed beams at the cracking and yield loads of the control unstrengthened beam as well as at those of the strengthened beam with nonprestressed CFRP reinforcement. The deflection in beams B00, B2-0%, B2-20%, B2-40%, and B2-60% at the cracking load 12.5 kN (2.8 kip) of beam B00 were 1.25 mm, 1.01 mm, 0.33 mm, 0.26 mm, and -0.25 mm (0.050 in., 0.040 in., 0.013 in., 0.010 in., and -0.010 in.), respectively. The deflection in beams B00, B2-0%, B2-20%, B2-40%, and B2-60% at the yield load 78.9 kN (17.7 kip) of beam B00 were 25.1 mm, 21.6 mm, 18.3 mm, 15.9 mm, and 15.6 mm (0.990 in., 0.851 in., 0.719 in., 0.625 in., and 0.614 in.), respectively. The deflection in beams B2-0%, B2-20%, B2-40%, and B2-60% at the cracking load 18.4 kN (4.1 kip) of beam B2-0% were 1.64 mm, 0.9 mm, 0.78 mm, and 0.27 mm (0.065 in., 0.036 in., 0.031 in., and 0.010 in.), respectively. The deflection in beams B2-0%, B2-20%, B2-40%, and B2-60%

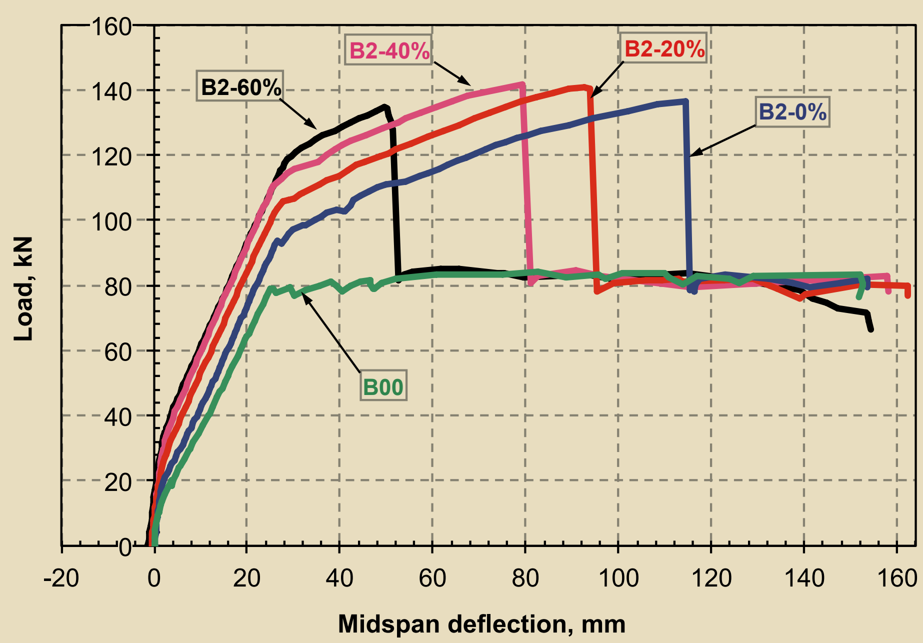


Figure 4. Load versus midspan deflection of all beams. Note: 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

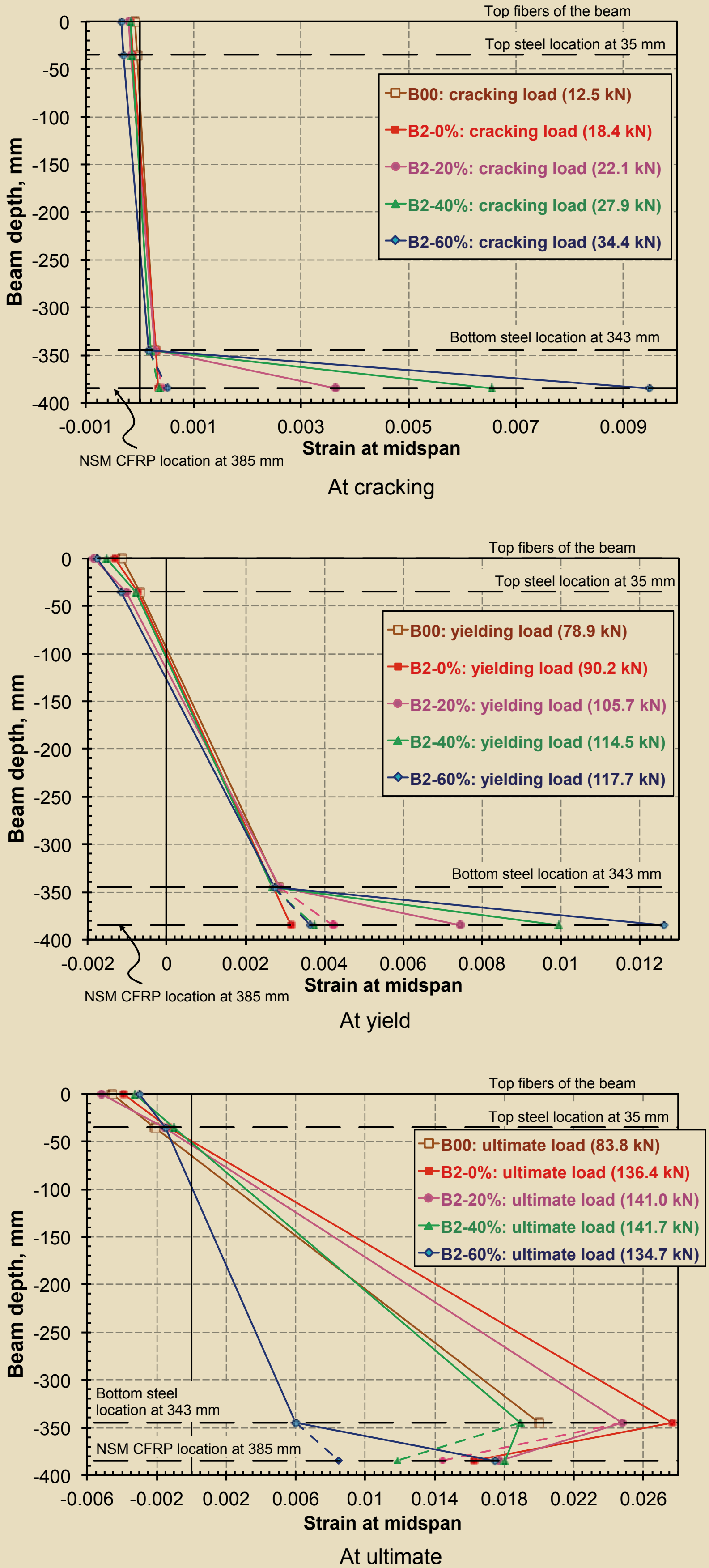


Figure 5. Strain distribution at midspan. Note: CFRP = carbon-fiber-reinforced polymer; NSM = near-surface-mounted. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

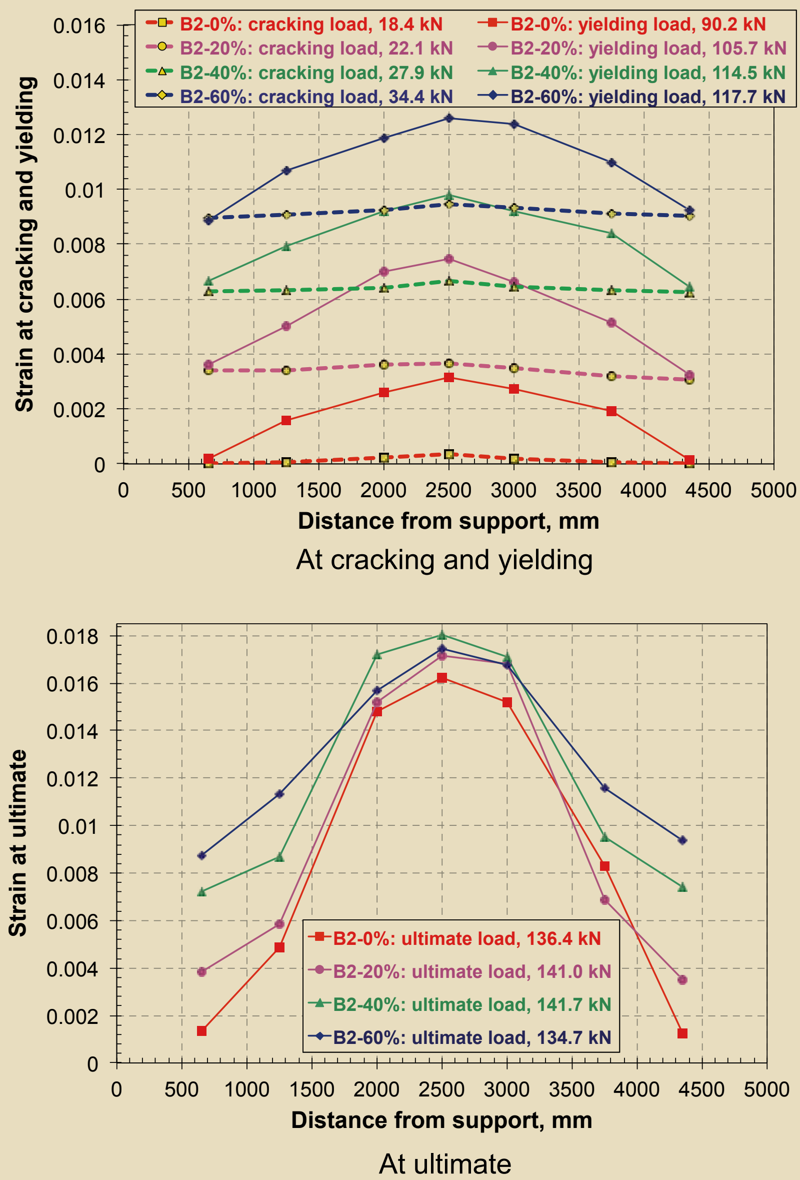


Figure 6. Strain profile along carbon-fiber-reinforced polymer reinforcement. Note: 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

at the yield load 90.2 kN (20.3 kip) of beam B2-0% were 25.27 mm, 22.0 mm, 19.31 mm, and 19.14 mm (0.995 in., 0.865 in., 0.760 in., and 0.754 in.), respectively.

Crack pattern and failure mode

The strengthened beams exhibited a typical flexural crack pattern. For beam B2-0%, no longitudinal cracks appeared on the soffit between the epoxy and the concrete except at the ultimate load. The epoxy cover spalled where the nonprestressed NSM CFRP bar ruptured (**Fig. 8**).

For the beams strengthened with prestressed NSM CFRP bars (B2-20%, B2-40%, and B2-60%), the first crack appeared at midspan. With increasing load, cracks appeared at the stirrup locations beginning at midspan. These cracks widened and new cracks formed between the stirrups. After yielding, no new cracks formed, but the existing cracks widened. No longitudinal cracks were visible at the epoxy-concrete interface or at the level of the bottom steel, indicating the effect of prestressing in the strengthened beams. For beams B2-20% and B2-40%, failure of the CFRP bar was accompanied by a loud sound (from rupture of the bar) and spalling of part of the epoxy cover at the rupture location.

Shortly after beam B2-60% yielded, failure occurred when the CFRP bar ruptured without any external signs, such as spalling of the epoxy. Further increases in loading after failure resulted in increased deflections, crack width, and depth, exposing the ruptured CFRP bar (Fig. 8).

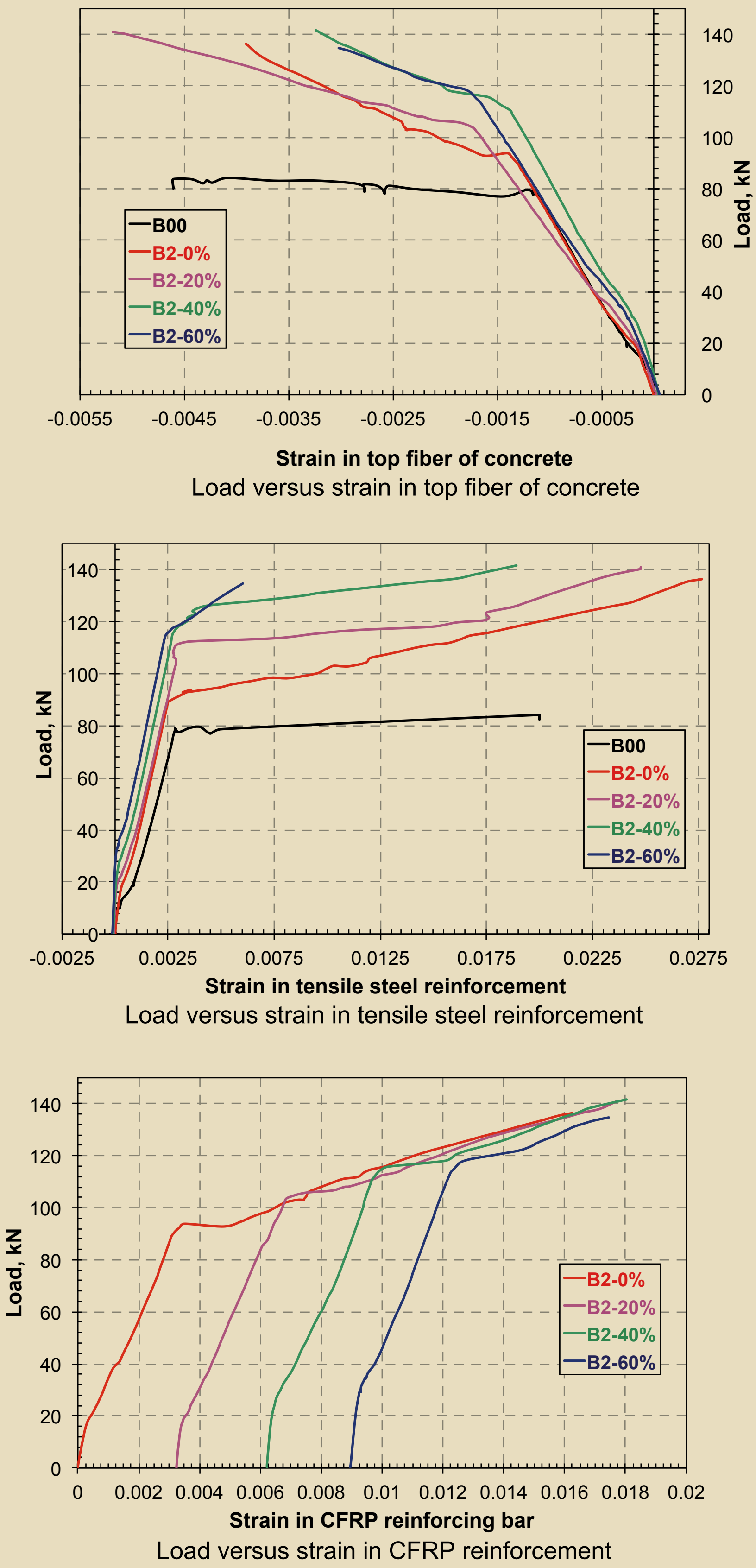


Figure 7. Load versus strain curves. Note: CFRP = carbon-fiber-reinforced polymer. 1 kN = 0.225 kip.

Table 2. Summary of experimental results for beams

Beam identification	f'_c, MPa	Δ_i* mm	P_{cr}, kN	Δ_{cr}, mm	P_y, kN	Δ_y, mm	P_u, kN	Δ_u, mm	μ	*En*, kN-mm
B00	45.5 ± 1.8	0	12.5	1.3	78.9	25.1	83.8	109.9†	4.37	8050
B2-0%	36.4 ± 2.7	0	18.4	1.6	90.2	25.3	136.4	114.5	4.53	11,899
B2-20%	40.7 ± 2.0	-0.5	22.1	1.5	105.7	27.7	141.0	92.5	3.34	9917
B2-40%	40.0 ± 0.5	-0.6	27.9	1.7	114.5	28.6	141.7	79.3	2.77	8669
B2-60%	36.0 ± 1.2	-1.3	34.4	2.4	117.7	28.2	134.7	49.7	1.76	4820

* The value of Δ_i has not been deducted from the values of Δ_{cr}, Δ_y, and Δ_u.

† This value is at the peak (ultimate) load and not at the unloading point at which the test was stopped because no further increase in the load occurred after the peak point.

Note: *En* = energy dissipated calculated as the area under the load-deflection curve; f'_c = average concrete compressive strength at time of testing the beams; P_{cr} = cracking load; P_u = ultimate load; P_y = yielding load; Δ_{cr} = midspan deflection at cracking; Δ_i = upward midspan deflection due to prestressing (camber); Δ_u = midspan deflection at ultimate; Δ_y = midspan deflection at yielding; μ = ductility index. 1 mm = 0.0394 in.; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

All strengthened beams failed by rupture of the CFRP bar after yielding of the tension steel reinforcement. No debonding or peeling at the end of the CFRP bars was observed. Keeping the mechanical anchors in place at the ends of the CFRP bars prevented peeling. For all prestressed beams, the concrete cover had to be removed after testing to expose the failure of the CFRP bar. **Figure 9** shows the final crack pattern of all beams.

Prestress losses

For beam B2-20%, the CFRP bar was prestressed to 29.3 kN (6.6 kip), causing an initial strain of 0.00346. The system was locked for one week before testing. The strain loss during that time was negligible, 0.00022, equivalent to a prestressing force of 1.87 kN (0.42 kip). Thus, at the time of testing the beam to failure, the effective prestress level was 19.44%.

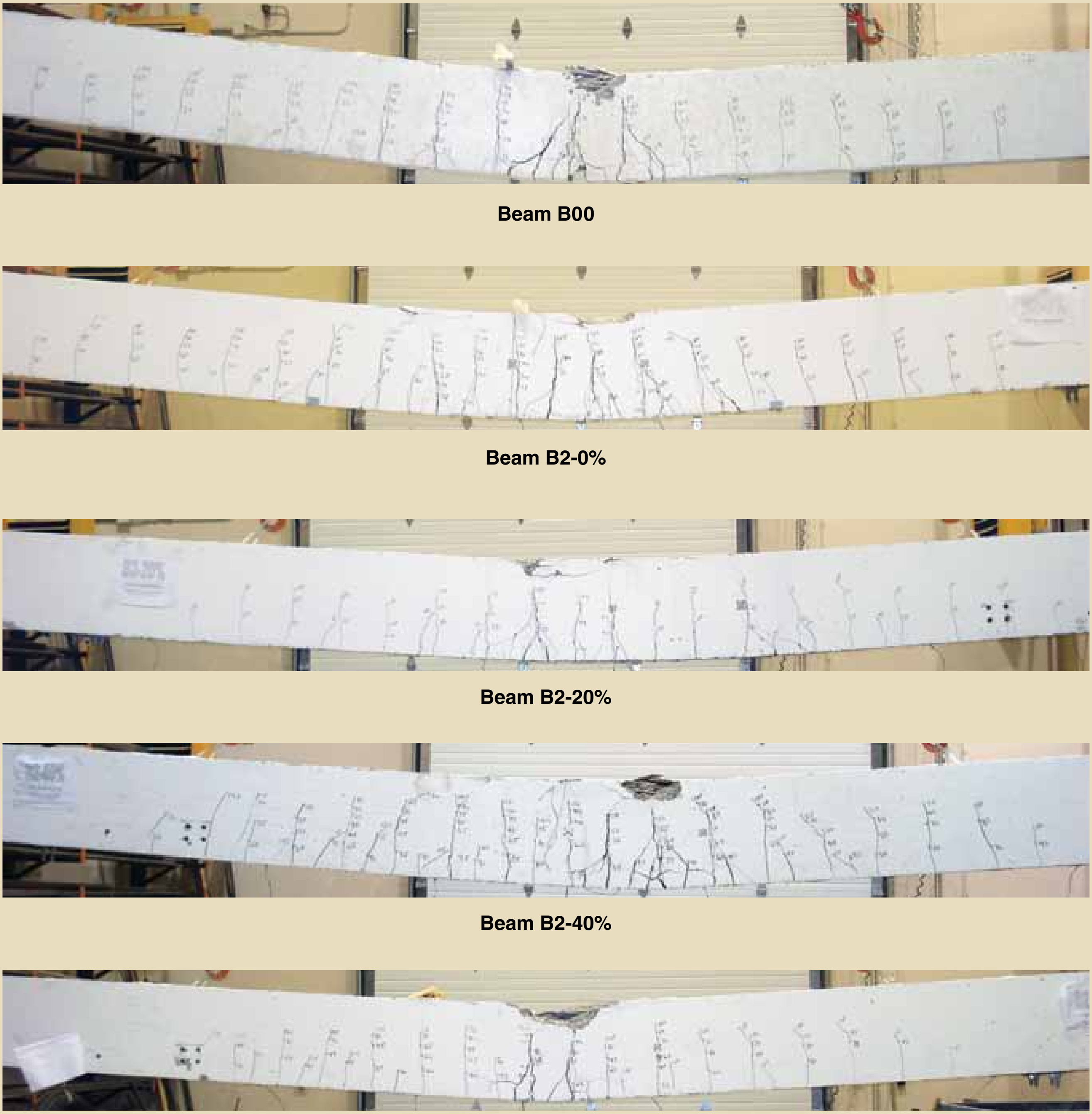
For beam B2-40%, the CFRP bar was prestressed to a force of 56 kN (12.6 kip), causing an initial strain of 0.00661. The system was locked for one week before testing. The strain loss during that period was 0.0004, equivalent to a prestressing force of 3.4 kN (0.76 kip). Thus, the effective prestress level was 37.25%.

For beam B2-60%, the CFRP bar was prestressed to a force of 84 kN (18.9 kip), causing an initial strain of 0.00991, and the system was locked for 24 hours. During prestressing, cracks formed around one of the anchor bolts at the fixed bracket (**Fig. 10**). After 24 hours, the cracks appeared wider, allowing some rotation in the fixed bracket, which led to some release in the prestressing force. The prestress loss at the jacking end was about 8 kN (1.8 kip), equivalent to a strain loss of 0.00094. Other than this strain loss, the average strain loss along the CFRP bar was found to be negligible, 0.00001, equivalent to a prestress loss of

Beam B2-0%

Beam B2-60%

Figure 8. Carbon-fiber-reinforced polymer rupture inside the groove.



Beam B00

Beam B2-0%

Beam B2-20%

Beam B2-40%

Beam B2-60%

Figure 9. Crack patterns for all beams.

0.085 kN (0.02 kip). At the time of testing the beam to failure, the total strain loss was 0.00095. Thus, the effective prestress level was 53.75%. In further research on similar strengthened beams, cracking of the concrete around the anchor bolts was avoided due to modifications made in the steel bracket of the anchorage system at the jacking end.

Strain distribution

Figure 5 shows the strain distribution at midspan along the depth of the beam at cracking, yield, and ultimate loads. For the strengthened beams with prestressed CFRP bars, the dotted lines connecting the strain in the bottom steel and the strain in the CFRP bar represent strain distribution excluding the effective strain due to prestressing (0.00324 for beam B2-20%, 0.00621 for beam B2-40%, and 0.00896 for beam B2-60%). At cracking, the strain distribution along the effective depth of the beams (depth from the extreme compression fiber to the centroid of the tension steel) was linear (Fig. 5). The large increases in

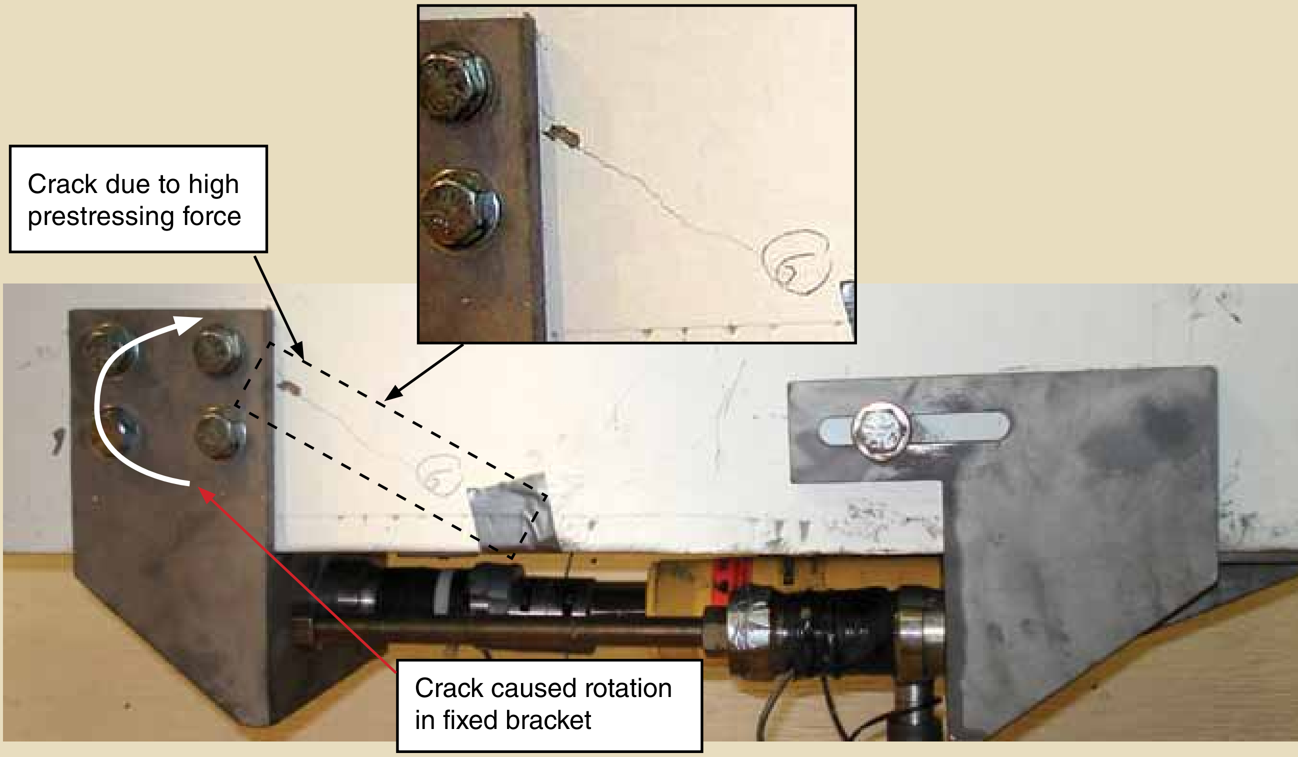


Figure 10. Cracks at jacking end while prestressing beam B2-60%.

strain in the CFRP bar are due to prestressing. At yield, the distribution along the effective depth of the strengthened beams with prestressed CFRP became nonlinear with the increased strains in the CFRP bars (Fig. 5), while for beam B2-0% the strain distribution remained almost linear.

At ultimate, for beam B00 the strain distribution at midspan is linear. For all strengthened beams, the strain distribution is nonlinear; the concrete in the top fibers began to crush before rupture of the CFRP bars. The strains in the concrete in beams B00, B2-0%, B2-20%, B2-40%, and B2-60% were 0.00461, 0.00391, 0.00519, 0.00344, and 0.00302, respectively. Although the concrete in beams B2-0%, B2-20%, and B2-40% exhibited high compressive strain, complete crushing was not observed until after the rupture of the CFRP bars.

At ultimate, for beams B00, B2-20%, B2-40%, and B2-60%, the strains in the compression steel were 0.0021, 0.00132, 0.00155, 0.001, and 0.00149, respectively. In beams B2-0%, B2-20%, and B2-40%, at ultimate, strain lag was observed between the tension steel and the CFRP bars. These beams exhibited significant increase in the strain in the tension steel at ultimate (0.02750, 0.02478, and 0.01891 in beams B2-0%, B2-20%, and B2-40%, respectively). The strain lag could be explained by the excessive yielding of the tension steel and some slippage of the CFRP bars. This lag might also be due to shifting of the strain gauges on the elongated CFRP bars during prestressing so that they were no longer aligned with the strain gauges on the tension steel. Because a crack occurred at midspan at the steel strain gauge location, the gauge read high strains, while the CFRP strain gauge had shifted inside the groove and therefore read lower strains. This shifting was observed during prestressing as the marks drawn at the location of the strain gauges at midspan of the CFRP bars visibly moved in the direction of prestressing.

All measured movements of the end anchor between the initial and final positions were almost identical to the calculated elongations along the length of the CFRP bars from the strain gauge measurements. In beams B2-20%, B2-40%, and B2-60%, the measured elongations in the 4365 mm, 4350 mm, and 4335 mm (171.85 in., 171.26 in., and 170.67 in.) long CFRP bars were 15 mm, 30 mm, and 45 mm (0.59 in., 1.18 in., and 1.77 in.), respectively. These elongations are equivalent to strains of 0.00344, 0.00690, and 0.01040 in beams B2-20%, B2-40%, and B2-60%, respectively, which are very close to the measured initial strains in the CFRP bars during prestressing (0.00346, 0.00661, and 0.00991, respectively). The recorded strains in the CFRP at failure of the beams were 0.01625, 0.01771, 0.01891, and 0.01745 for beams B2-0%, B2-20%, B2-40%, and B2-60%, respectively (Fig. 5).

Strain profile along the CFRP bars

Figure 6 shows the strain profile along the length of the CFRP bars at cracking, yielding, and ultimate loads. For all beams, the strains were highest at midspan.

Table 3. Comparing experimental results for strengthened beams with results of B00

Beam identification	P_{cr}, %	Δ_{cr}, %	P_y, %	Δ_y, %	P_u, %	Δ_u, %
B2-0%	47.80	31.4	14.3	0.5	62.7	-4.2
B2-20%	77.03	18.8	34.0	10.1	68.2	-15.8
B2-40%	123.90	36.2	45.1	13.8	69.0	-27.9
B2-60%	176.40	95.3	49.1	12.1	60.8	-54.8

Note: P_{cr} = cracking load; P_u = ultimate load; P_y = yielding load; Δ_{cr} = midspan deflection at cracking; Δ_u = midspan deflection at ultimate; Δ_y = midspan deflection at yielding.

Table 4. Comparing experimental results for strengthened beams with results of B2-0%

Beam identification	P_{cr}, %	Δ_{cr}, %	P_y, %	Δ_y, %	P_u, %	Δ_u, %
B2-20%	19.8	-9.6	17.2	9.5	3.4	-19.2
B2-40%	51.5	3.7	27.0	13.2	3.9	-30.8
B2-60%	87.0	48.6	30.5	11.5	-1.2	-56.6

Note: P_{cr} = cracking load; P_u = ultimate load; P_y = yielding load; Δ_{cr} = midspan deflection at cracking; Δ_u = midspan deflection at ultimate; Δ_y = midspan deflection at yielding.

For beam B2-0%, the strains were almost zero at the ends of the CFRP bar. This showed the contribution of the epoxy in transferring the force from the concrete to the CFRP bar. At higher loads, longitudinal cracks appeared at the soffit of the beam, indicating that the epoxy had started to fail. The presence of the mechanical anchors at both ends of the CFRP bar prevented debonding either between the CFRP bar and the epoxy or between the epoxy and the concrete, as the anchors would have carried the tension force.

For beams B2-20% and B2-40%, the strains near the anchors remained almost constant during the test, indicating the effectiveness of the epoxy in transferring the forces between the prestressed CFRP bar and the concrete. There was no slippage at the ends of the CFRP bars at release. However, for beam B2-60%, there was a slight loss of strain in the CFRP bar at the jacking end due to slippage at transfer. The strain profile showed no debonding or fracture in the epoxy-concrete interface during testing.

Load-strain in concrete, steel, and CFRP

Figure 7 shows the relation between load and the strains in the concrete, tension steel, and CFRP bar. The strain in the compression steel was almost linear to failure without yielding except in the unstrengthened beam.[31] After cracking, the load-strain behavior in the concrete was linear until yielding of the bottom reinforcement, after which the flexural stiffness of the beams was reduced. Load-strain behavior for both the bottom steel and the CFRP was linear until cracking. The flexural stiffness of the beam was reduced, but the curves remained linear at a lower slope up to yield of the bottom steel, after which the curve was nonlinear up to rupture of the CFRP bar.

Due to prestressing, the concrete had an initial tensile strain (0.0225×10^{-3}, 0.045×10^{-3}, and 0.055×10^{-3} in beams B2-20%, B2-40%, and B2-60%, respectively) while the tension steel reinforcement was initially under compressive strain (-0.059×10^{-3}, -0.094×10^{-3}, and -1.23×10^{-3} in beams B2-20%, B2-40%, and B2-60%, respectively). These small values of strain in concrete and tension steel reinforcement are not clearly visible in Fig. 7. In beams B2-20%, B2-40%, and B2-60%, the CFRP reinforcement had a net initial tensile strain of 0.00324, 0.00621, and 0.00896, respectively, after loss of prestress.

Effect of prestress on flexure

To evaluate the effect of prestress on the overall flexural behavior, the loads and deflection of the strengthened prestressed beams were compared with the control beam B00 (**Table 3**) and with the nonprestressed beam B2-0% (**Table 4**). The nonprestressed beam B2-0% was also compared with the control beam. **Figure 11** shows the effect of increasing the prestressing level on the cracking, yielding, and ultimate loads with respect to the control beam B00 and the nonprestressed strengthened beam B2-0%. Increasing the prestressing levels significantly increased the cracking loads and slightly increased the yielding loads but had almost no effect on the ultimate loads except for the slight reduction in the ultimate load of beam B2-60%. This beam had an ultimate load 1.2% less than B2-0%.

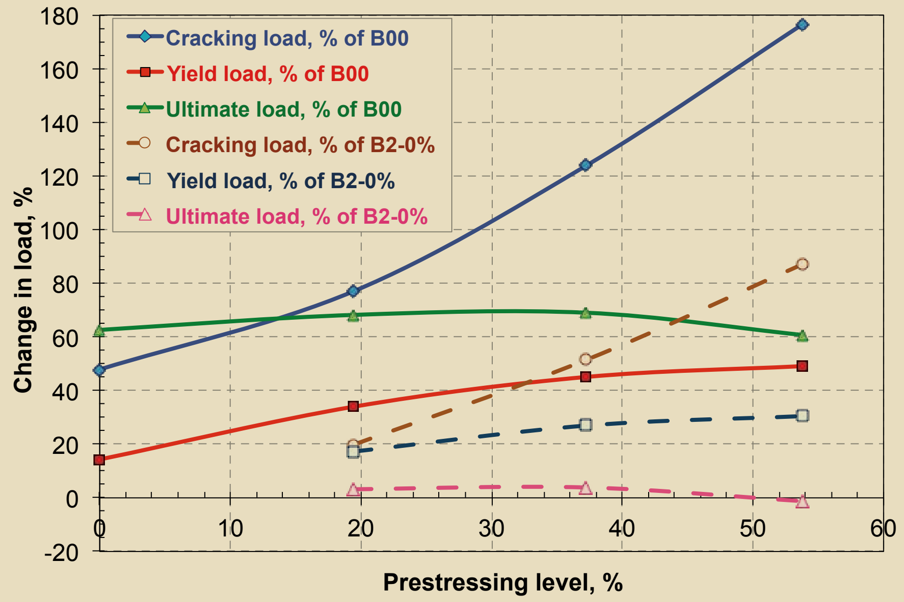


Figure 11. Effect of prestressing level on the loads as percentage of control and nonprestressed strengthened beams.

Figure 12 presents the effect of increasing the prestressing levels on the deflection at cracking, yielding, and ultimate loads. When compared with the control beam B00 and the nonprestressed beam B2-0%, at prestress levels above 20% the deflection at cracking loads increased significantly. Prestressing decreased the deflections at ultimate load compared with beams B00 and B2-0%. The effect on deflection at yield was negligible compared with beams B00 and B2-0%.

Increasing the prestressing level decreased the ductility index of the beams (calculated as the ratio between the deflection at ultimate load and the deflection at yielding of steel [Table 2]).

Figure 13 shows the relation between the prestressing level and the ductility of the beams based on the energy approach calculated from the area under the load-deflection curve at the time of rupture of the CFRP bars. The ductil-

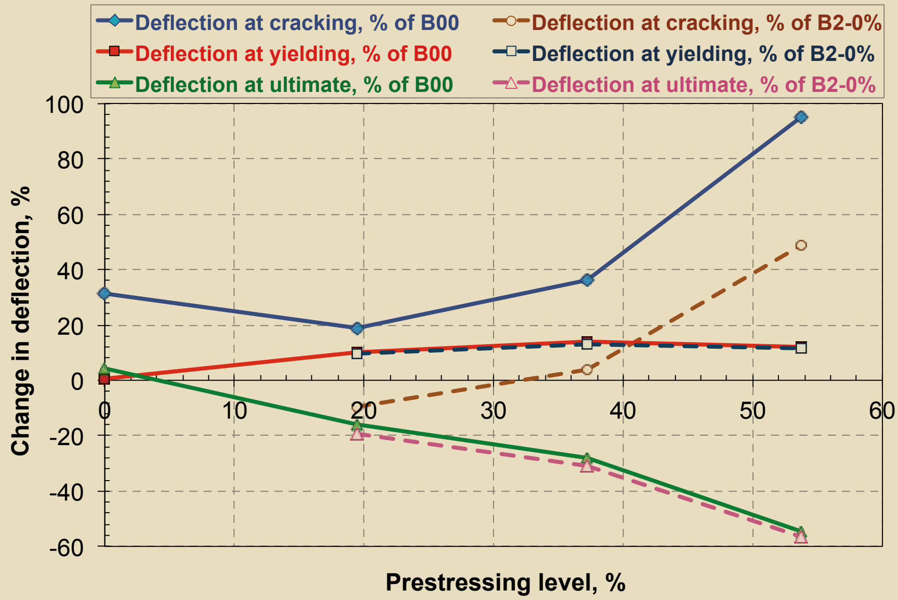


Figure 12. Effect of prestressing level on the deflection, percentage of control and nonprestressed strengthened beams.

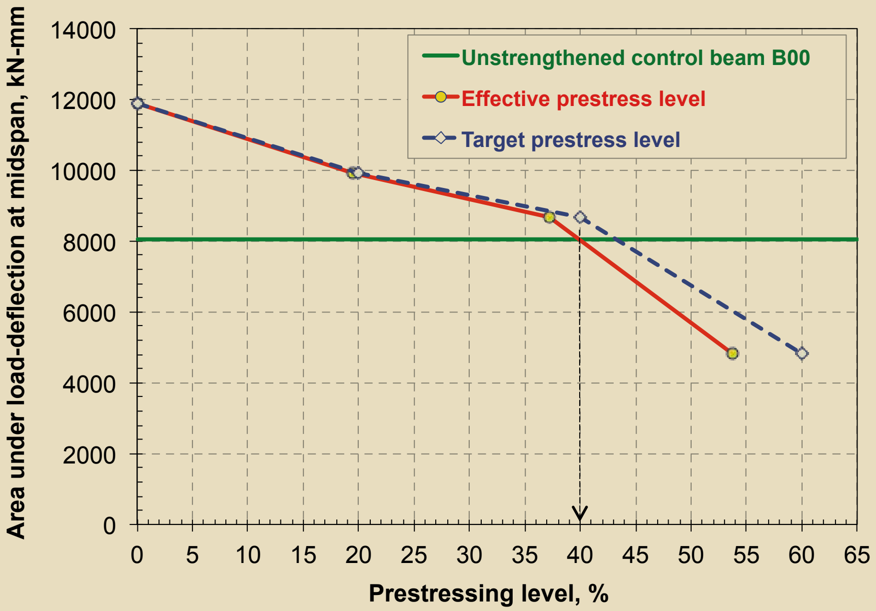


Figure 13. Effect of prestress on ductility of beams. Note: 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

ity of the control beam B00, shown for comparison, is calculated from the area under the load-deflection curve up to the ultimate load of 83.8 kN (18.8 kip) and a deflection of 109.9 mm (4.33 in.) when the crushing of the concrete occurred at strain 0.00461. The optimum prestressing level was determined to be about 40% to maintain the beam's original ductility before strengthening and to simultaneously take advantage of the prestressing effect applied to the system.

Conclusion

Flexural strengthening of reinforced concrete beams using near-surface mounted (NSM) CFRP bars has proved to be efficient. By inducing prestressing in the NSM CFRP bars, the system significantly improved the performance of the beams. When compared with the control unstrengthened beam, prestressed CFRP enhanced overall performance by decreasing deflections and crack widths; delaying the formation of new cracks; and increasing the cracking, yielding, and ultimate loads.

In general, increasing the prestressing levels of the NSM CFRP reinforcement improved the overall flexural behavior of the beams at service and ultimate conditions, but also decreased the ductility of the beams when compared with the control beam and the beam strengthened with nonprestressed NSM CFRP.

All strengthened beams failed after yielding of the tension steel reinforcement due to rupture of the NSM CFRP bars with no debonding. For all strengthened beams with prestressed NSM CFRP bars, the concrete cover was removed to observe the rupture failure of the CFRP bars. Keeping the mechanical anchors at the ends of the NSM CFRP bars enhanced the beams' behavior by preventing any possible debonding or peeling failure at the ends.

Prestress losses recorded between the time of prestressing and the time of testing the beams were very small and considered negligible. In some cases while unlocking the system there was some loss due to movement of the steel anchor, but the effect was localized at the jacking end of the beam and did not affect the behavior of the beams.

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Notation

a = variable length depending on the elongation

En = energy dissipated calculated as the area under the load-deflection curve

f'_c = average concrete compressive strength at time of testing the beams

$f_{CFRP,u}$ = ultimate tensile strength of CFRP bar

L = total length of CFRP bar

P_{cr} = cracking load

P_u = ultimate load

P_y	= yielding load		Δ_y	= midspan deflection at yielding
Δ_{cr}	= midspan deflection at cracking		μ	= ductility index
Δ_i	= upward midspan deflection due to prestressing (camber)			
Δ_u	= midspan deflection at ultimate			

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Synopsis

Near-surface-mounted (NSM) fiber-reinforced polymer (FRP) is an efficient system for strengthening reinforced concrete beams. The FRP is embedded in grooves in the concrete cover on the tension side of the member. When the FRP is not prestressed, the system can support additional loads applied to the structure but is unable to carry the dead load. Previous researchers showed that premature failure may occur in beams strengthened with nonprestressed NSM FRP, leading to failure in beams without reaching the full designed capacity.

This paper reports the findings of an experimental investigation into the effectiveness of using prestressed NSM carbon FRP (CFRP) bars to strengthen reinforced concrete beams. The effect of varying the prestressing levels in the CFRP bars on the behavior of the beams was examined. Five large-scale reinforced concrete beams were tested: one control, one strengthened with nonprestressed NSM CFRP bars, and three strengthened with NSM CFRP bars prestressed to 20%, 40%, and 60% of the ultimate strength of the CFRP. The flexural behavior of the prestressed concrete beams is compared with the nonprestressed beam and the control.

Test results showed that all prestressed concrete beams failed due to rupture of the CFRP bars without any premature or debonding failure. Prestressing the embedded NSM CFRP reinforcement enhanced the overall performance of the beams by increasing the loads at cracking, yielding, and ultimate. Due to the prestressing effect, the deflections in the strengthened beams corresponding to the cracking, yielding, and ultimate loads of the unstrengthened beam are less than the deflections at the same loads of the unstrengthened beam as well as at those of the strengthened beam with nonprestressed CFRP reinforcement.

Keywords

Anchorage, carbon-fiber-reinforced polymer, CFRP, ductility, flexure, static.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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