STRENGTHENING OF CONCRETE BEAMS WITH MECHANICALLY FASTENED FRP STRIPS

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Abstract

The current method of flexurally strengthening reinforced concrete members involves bonding fiber reinforced polymer (FRP) strips, which requires extensive time and skilled labor. An alternative method is being developed which uses powder actuated fastening systems to attach the FRP strips to the concrete surface. Powder actuated tools are inexpensive, readily available, and do not require sophisticated training to operate. The fasteners must be attached in a certain manner as not to destroy the concrete substrate, which reduces fastener strength and reduces the durability of the concrete member. This paper presents the initial experimental and analytical research from the investigation of this method on full-scale reinforced concrete T beams.

Introduction

A technology to rapidly strengthen and repair bridges for both military and civilian uses is needed. In a military environment this technology is needed to rapidly strengthen concrete bridges that are damaged or become unserviceable due to low load ratings, and consequently adversely impact the military's operational mission. In the civilian sector there exists an equal need to rapidly strengthen and repair highway bridges, as it is undesirable to close down a bridge for any length of time.

A method of strengthening reinforced concrete beams by attaching FRP strengthening strips to the bottom surface using powder-actuated fasteners has been developed. This method is a rapid procedure that utilizes simple hand tools, lightweight materials, and unskilled labor. Unlike the conventional method of adhesively bonding FRP strips to the concrete surface, this method does not require significant surface preparation, and allows for the immediate use of the strengthened concrete structure.

The current method used to strengthen reinforced concrete beams is to adhesively bond strips of thin composite laminates, also known as fiber reinforced polymer (FRP) strengthening strips, to the surfaces of these beams to increase their capacity. Typically these strips are attached to the soffits to increase the flexural capacity of the reinforced concrete element. This method is time-consuming since it can take days per application to sand blast, clean, and smooth the concrete to make it suitable for bonding the strip. Following the application of the adhesive, the FRP strengthening strip "must not be disturbed for a minimum of 24 hours" according to one supplier of strengthening strips (SIKA 1999).

A number of authors have recommended that to prevent a catastrophic brittle failure of a beam strengthened with a bonded strip, mechanical anchorage should be provided at the strip ends (Spadea at al. 1998, Garden and Hollaway 1998). Plate end anchorages have a greater effect in beams that are shorter, with a high ratio of shear force to bending moment, than in longer beams. Anchorage is usually provided by anchor bolts or bonded cover plates (Hussain et al. 1995).

The method of strengthening reinforced concrete beams by mechanically attaching an FRP strip not only has the advantage of being rapid, but also provides the necessary anchoring mechanism as part of the procedure. The use of multiple small fasteners as opposed to large diameter bolts distributes the load more evenly over the strip.

Background

A powder actuated fastening system drives a fastener into a concrete substrate. As the fastener penetrates the concrete is compressed as material is displaced. When the fastener is driven into the concrete, the surface of the fastener becomes deformed and generates friction with the surrounding material. The heat generated in this process causes sintering and creates a bond between the concrete and fastener (CEB 1994). These two factors give the fastener its holding capacity. Driving the fasteners into a predrilled hole greatly reduces the amount of cratering and spalling that occurs in the surface of the concrete when the fastener first enters. Tests were performed to determine load capacity per fastened connection, which was determined to be 4,448 N (1,000 lbs) (Lamanna et al. 2001a).

A preliminary investigation into the feasibility of mechanically attaching the strengthening strip was first conducted on 35 small-scale reinforced concrete beams. The beams measured 152 x 152 x 1,219 mm (6 x 6 x 48 in.) and were tested in four-point bending on a span of 1,067 mm (42 in.) with a moment span of 203 mm (8 in.). A variety of fasteners and fastener layouts were considered with a number of different strengthening strips, including steel. The strengthened small-scale beams showed increases in yield and ultimate moments up to 36% and 30%, respectively, over the unstrengthened control beams (Lamanna et al. 2001b).

The effect of increasing the scale of the proposed method was then investigated on 15 large-scale. The size of most components of the method, the FRP strip, the concrete cross section, the reinforcing steel, can all be increased; however, the fasteners are a fixed diameter and penetrate the same depth into the concrete regardless of beam size. The beams measured 305 x 305 x 3,658 mm (12 x 12 x 144 in.) and were tested in four-point bending on a span of 3,353 mm (132 in.) with a moment span of 1,118 mm (44 in.). Different types of FRP strengthening strips, fasteners, and fastener layouts were examined. The large-scale beams strengthened with mechanically fastened beams showed increases in yield and ultimate moments up to 14% and 20%, respectively, over the unstrengthened control beams, and exhibited a behavior as ductile as a beam strengthened using the bonded method (Lamanna et al. 2001a). The failure mechanism of the beams configured to obtain the greatest amount of strengthening was concrete compression failure, similar to the failure mechanism of an unstrengthened reinforced concrete beam.

The first two series of beam tests were conducted on smaller than full size beams for reasons of economics and for ease of handling in the laboratory. A set of nine full size T beams was then tested to investigate the effects of increasing the size even further and to examine the strengthening effect on T beams. The tests were conducted on beams with three different amounts of tensile reinforcement; 1,935.5, 3,225.8, and 5161.3 mm^2 (3, 5, and 8 in^2). The three beams with the lightest amount of tensile reinforcement are discussed in this paper. All nine beams will be discussed elsewhere.

Materials

The FRP composite materials strengthening strips used were custom designed as an earlier part of this research and were pultruded by Strongwell (Chatfield Division) for this portion of the research and trademarked under the name SafStrip™. The strips were tested according to ASTM D3039, and modulus and tensile strength were determined to be 56.3 ± 4.9 GPa (8,158 ± 709 ksi) and 655 ± 43 MPa

(95.0 ± 6.2 ksi). The strips had a cross section of 102 x 3.2 mm (4 x 0.125 in.) and were pultruded in 9.144 m (30 ft) lengths. The strips were coiled in approximately 1,220 mm (4 ft) diameter rolls for transportation.

The full-scale T beams were 762 mm (30 in.) deep, with a stem thickness of 305 mm (12 in.) and a web depth and width of 203 mm and 1,524 mm (8 and 60 in.). They were cast at the US Army Engineer Research and Development Center in Vicksburg, Mississippi with concrete supplied by a local vendor. A maximum aggregate size of 51 mm (2 in.) was used with a 76 mm (3 in.) slump. The measured concrete strength at 28 days was 31.5 MPa (4,566 psi).

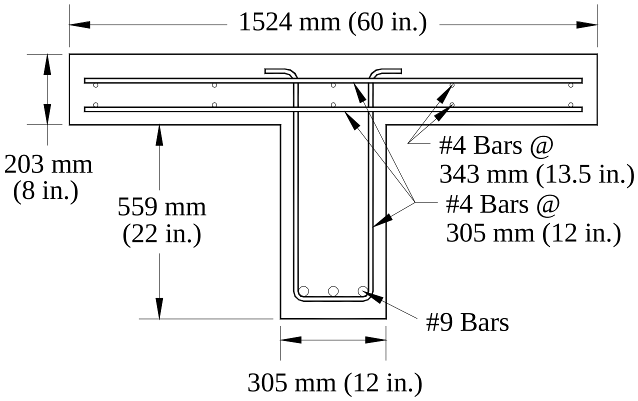

Figure 1. Internal steel layout of T beams.

The primary tension steel was provided by three #9 Grade 60 deformed bars. Two layers of #4 bars were provided in the flange to control temperature and shrinkage cracking. Shear reinforcement was provided in the form of open stirrups of #4 bars spaced at 305 mm (12 in.). Figure 1 shows the internal steel layout, and Figure 2 shows a T beam after removed from the formwork. The beams were 8.84 m (29 ft) long, and were tested in four-point loading on an 8.53 m (28 ft) span, with a 1.52 m (5 ft) moment span. The beams were cycled to roughly 60 percent of their yield strength five times before they were tested for this study.

The fastening system used was a Hilti DX A41 Powder Actuated Fastening system. The DX A41 uses a 6.8 mm (0.27 in.) caliber short gunpowder booster. Purple boosters, signifying extra heavy charge, were used in conjunction with X-AL-H 47P8 fasteners, which had a 47 mm (1 7/8 in.) shank length and a 4.5 mm (0.177 in.) shank diameter. Pre drilling was performed with a DX-Kwik bit, which had a diameter of 4.76 mm (0.188 in.) and a drill bit length of 15.88 (0.625 in.). A standard hammer drill was used with this special bit.

Figure 2. A T beam after it was removed from the formwork.

Neoprene backed 18 mm (0.71 in.) washers were used with each fastener to prevent the FRP from being damaged by the nail head and to increase the bearing strength by providing a clamping pressure around the fastener. A 50.8 mm (2 in.) spacing was used between the fasteners along the length of the beam, as well as between the rows of fasteners. Beam A3-1 was strengthened with a single strip, with the end set of fasteners was located 482.6 mm (19 in.) from the support. Beam A3-2 was strengthened with two strips, one on top of each other, to make the total strip thickness 6.35 mm (0.25 in.), and the end set of fasteners was located 76.2 mm (3 in.) from the support. Beam A3 was the unstrengthened control beam.

Attachment Procedure

The reinforced concrete T beam was placed on the supports, and braced horizontally at the supports along the edge of the flange to keep the beam upright. Fastener locations were marked on the strengthening strip. The strip was centered on the bottom of the web of the beam and held in place with carpenters' clamps. The strip was secured at mid span by pre drilling the four fastener locations closest to the centerline, then driving the fasteners into the predrilled holes. Then, working from the mid span toward one support, holes were predrilled then fastened in sets of four until half of the strip was attached. Then the process was repeated form the mid span to the other support. It took two researchers a total of five man-hours to attach the strip. Figure 3 shows a fastener being driven to attach the strip.

Local spalling was observed in instances where a fastener hit a rebar chair or encountered a large aggregate. This spalling was seen around only a few, separated fasteners, and was not seen to be a problem since multiple redundant fasteners were used. Some spalling was also observed if the fastener encountered pockets of poor concrete consolidation. The spalling itself was not considered a problem, but these fasteners tended to become overdriven, causing the washer to crush and locally damage the FRP strip around the fastener.

Figure 3. Fastener being driven to attach the strip.

Experimental Testing

Two LVDTs were used to measure the deflection of the flange at midspan. An MTS Testar system was used to control the two 490 kN (110 kip) actuators, one at each load point. An Optim Megadac was used for data collection. The beams were loaded at the rate of 2.5 mm/min. (0.1 in./min.). All beams were put through five cycles of loading from zero to 464.4 kN-m (342.5 ft-k) to allow additional researchers the opportunity to collect deflection behavior data. The beams were then tested to failure. Data is reported for a deflection to 63.5 mm (2.5 in.), which corresponds to a deflection of about L/135. A discussion of the ultimate behavior of the beams will be reported elsewhere.

Experimental Results And Discussion

The control beam A3 yielded at a moment of 477 kN-m (352 ft-k) and reached a moment of 574 kN-m (423 ft-k) at a stroke of 63.5 mm (2.5 ft). Beam A3-1, strengthened with one strip, yielded at a moment of 515 kN-m (380 ft-k) and reached a moment of 656 kN-m (484 ft-k) at a stroke of 63.5 mm (2.5 in.). Beam A3-2, strengthened with two strips, yielded at a moment of 533 kN-m (393 ft-k), and reached a moment of 730 kN-m (538 ft-k) at a stroke of 63.5 mm (2.5 in.). Beams A3-1 and A3-2 showed increases in yield moment of 8.0% and 11.7% over the control beam. Beams A3-1 and A3-2 showed increases in moment at a stroke of 63.5 mm (2.5 in.) of 14.4% and 27.2% over the controls. Figure 4 shows the moment-stroke curves for beams A3, A3-1 and A3-2.

The two strengthened beams both showed increased moments at yield and 63.5 mm (2.5 in.) stroke moments. All three beams developed flexural cracks that began in the bottom of the web and progressed up into the compression flange. The pre-yield stiffness for all three beams is similar. This is due to the small axial stiffness, EA, of the FRP strip relative to the rebar. After yield, the stiffness for the two strengthened beams is greater than that of the control beam. This is because the EA of the steel is drastically reduced after the steel has yielded. The EA of the double strip on beam A3-2 is twice the EA of the single strip on beam A3-1, but the increase in stiffness is not double because the steel still has some residual stiffness.

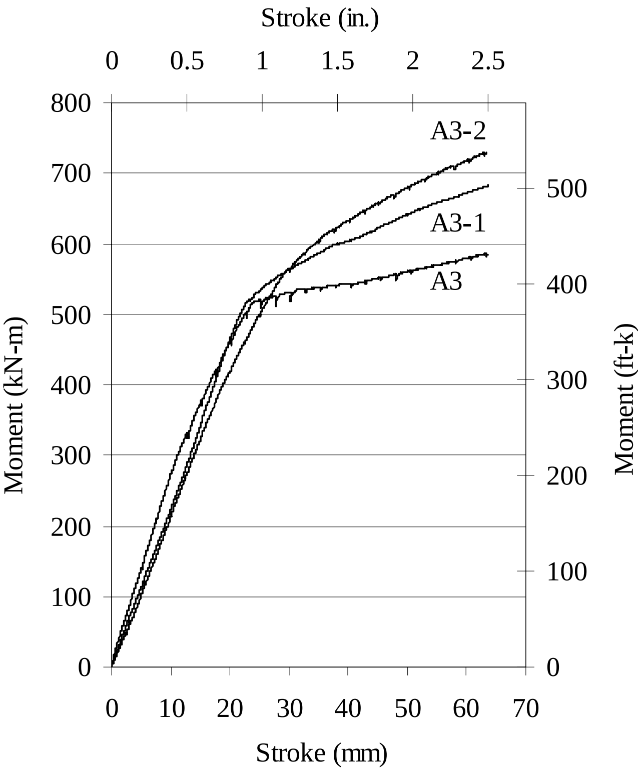

Figure 4. Moment-stoke curves for beams A3, A3-1, and A3-2.

Analytical Modeling

The moment-curvature model utilizes equilibrium, strain compatibility of the sections involved, and the constitutive relations of the materials. The concrete is modeled after the constitutive relationship outlined in Park and Paulay (1975), the FRP is modeled linearly until failure, and the steel rebars are modeled as bilinear, having a post yield stiffness 1.7 percent of the elastic stiffness. The assumptions made in this model are:

1. Plane sections remain plane during bending. This means there exists a linear variation in strain over the cracked concrete cross section, which is supported by strain data obtained during the large-scale testing, and appears to be valid even after the reinforcing steel has yielded. This assumption also neglects the effect of slip between the FRP strip and the concrete.
2. The concrete in tension behaves linearly up until rupture, and then carries no load.
3. There is uniform stress and strain throughout the cross section of the strip. This assumption ignored shear lag by assuming there is no variation in stress across the width of the strip. This also means that the strip acts as a tensile component and does not bend.
4. The strengthening strip does not affect shear strength. This neglects any increase in shear capacity though dowel action of the strip. Dowel action is usually neglected when determining shear strength of FRP reinforced concrete members (ACI 440F and ACI 440H). This assumes the cracks formed from attaching the strip are small enough to maintain aggregate interlock.

These four assumptions are typical of moment-curvature models for predicting the behavior of reinforced concrete beams strengthened with an adhesively bonded FRP strip. A good example of a moment-curvature model which uses these assumptions to develop the moment-curvature curves for beams with adhesively bonded FRP strips is given in An et al. (1991). The strain in the top fiber of the concrete in compression is increased incrementally, and the theory is used to develop moment-curvature pairs. The strain in the top fiber is increased until reaching the crushing strain of 0.0038. To use this type of moment-curvature model for mechanically fastened FRP strips, two more assumptions must be made:

5. The fasteners in the shear span transfer the entire load between the concrete and the FRP strip. This assumption is supported by the strain distributions obtained during the large-scale testing.
6. The end set of fasteners must transfer the forces between the concrete surface and the FRP strip at this point along the length of the beam in order for assumption 1 to remain valid. For a beam in four point bending, this means that the farther away from the support that the end set of fasteners is located, the greater the force this set of fasteners must transfer.

The moment-curvature model was used to develop moment-curvature pairs. At each moment, the force tensile force in the FRP strip was calculated, and then the tensile force was divided by the number of fasteners in one shear span to calculate the force per fastener. If the force per fastener exceeded the fastener strength, then the beam would fail by strip delamination.

The end set of fasteners needed to be checked as well. The location of the end fasteners in a beam strengthened with a mechanically fastened FRP strip can be the cause of the beam failing by strip detachment before the concrete crushes in compression. A close up of the region of a strengthened beam near the support is shown in Figure 5. The section between the end fasteners and the support is unstrengthened, even though the FRP strip continues past the end fasteners and the support. The strip in this region is not connected to the concrete, and does not interact with the section in this region. The section from the end fasteners to the interior of the beam is strengthened, as the FRP strip is attached with fasteners throughout the length.

At the location of the second fasteners, a distance $a_f + s_f$ from the support, there is an applied moment M_f, caused by the applied moment in the moment span of the beam. The farther the end fasteners are from the support, the greater the applied moment M_f at the second fasteners will be. The strengthened section must carry this moment. Under this applied moment, just to the right of the second fasteners, the tensile force developed in the FRP strip must be transferred to the concrete beam only through the end fasteners. The force per end fastener can be found by dividing the force in the

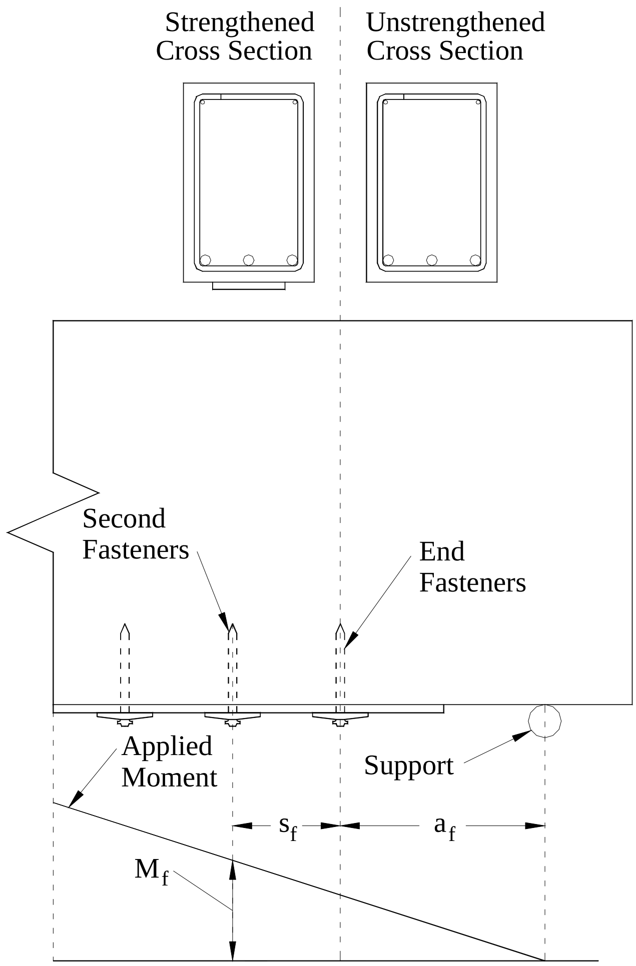

Figure 5. Close up of end fastener distance and applied moment diagram.

strip at a moment on the section of M_f by the number of end fasteners. If the force per end fastener is greater than the strength per end fastener, the beam will fail by strip delamination initiated by failure of the end fasteners. The modified process for developing the moment-curvature behavior for a beam strengthened with a mechanically fastened FRP strip is shown in a flow chart in Figure 6.

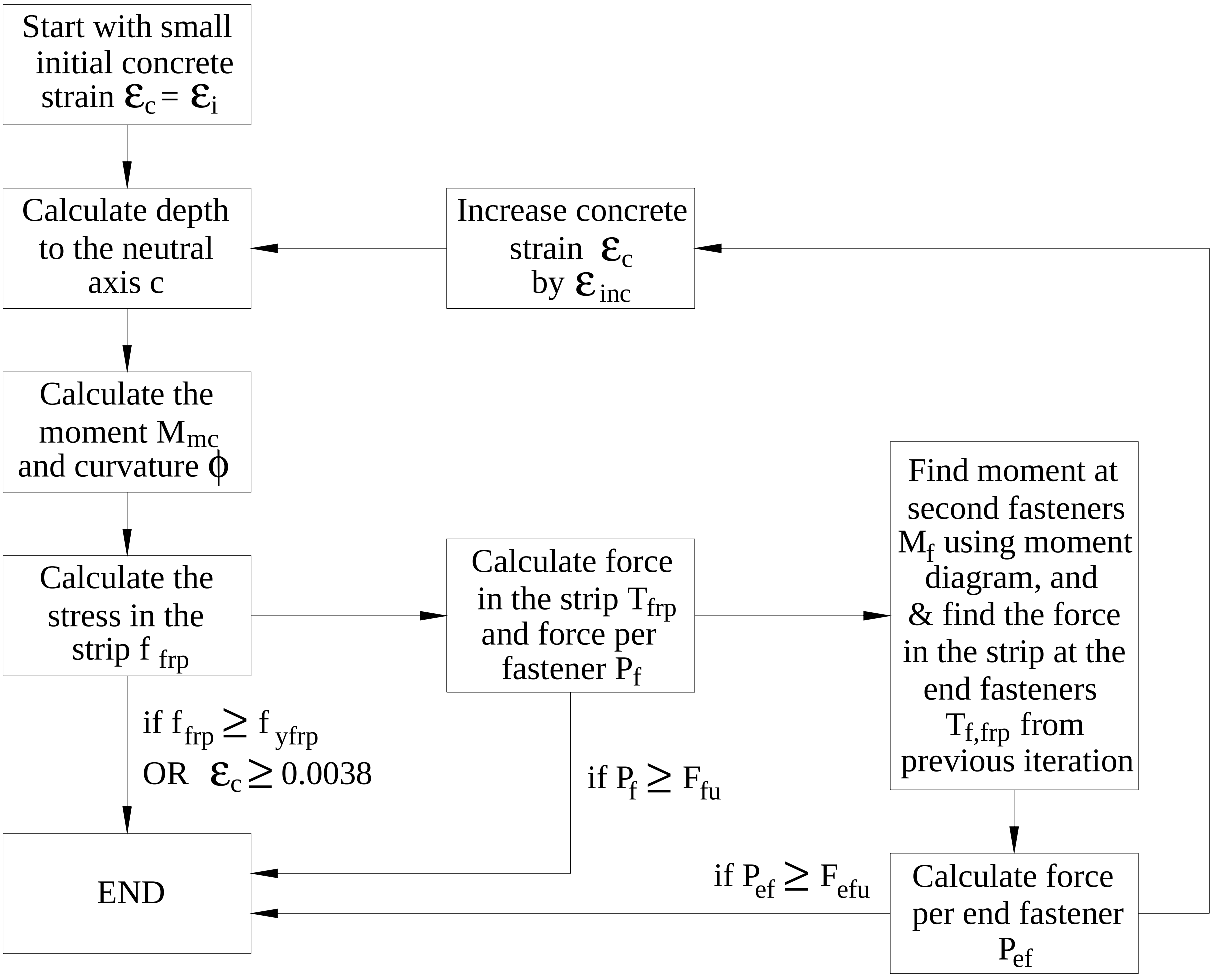

Figure 6. Flow chart showing the procedure for predicting the moment-curvature behavior of a beam strengthened with a mechanically fastened FRP strip.

The moment-deflection behavior was predicted using a virtual work approach. The deflection at the mid span of the beam can be calculated by

$$\delta_{midspan} = \int_0^L m(x)\,\phi(x)\,dx \tag{1}$$

where m(x) is the moment diagram from a virtual unit load applied downward at the mid span, and $\phi(x)$ is the curvature along the length of the beam. The curvature along the length of the beam is found by using the moment diagram and the moment-curvature model.

Analytical Versus Experimental Comparison

The experimental and calculated yield moment and yield deflection for the A3 T beams are compared in Table 1. It can be seen that the analytical model over predicts the yield moments for all three beams, having calculated / experimental values around 1.09. The analytical model closely predicts the yield deflection for the three beams. The experimental and analytical predictions for the moment-deflection are shown in Figure 7.

Table 1. Experimental and calculated yield moment and deflection for the T beams.

Beam	Experimental Yield Moment		Calculated Yield Moment		Calc / Exp	Experimental Yield Deflection		Calculated Yield Deflection		Calc / Exp
	(kN-m)	(ft-k)	(kN-m)	(ft-k)		(mm)	(in.)	(mm)	(in.)	
A3	477	352	524	386	1.09	24.1	0.95	24.2	0.95	1.00
A3-1	515	380	555	409	1.08	24.1	0.95	24.9	0.98	1.03
A3-2	533	393	586	432	1.10	26.7	1.05	24.9	0.98	0.93

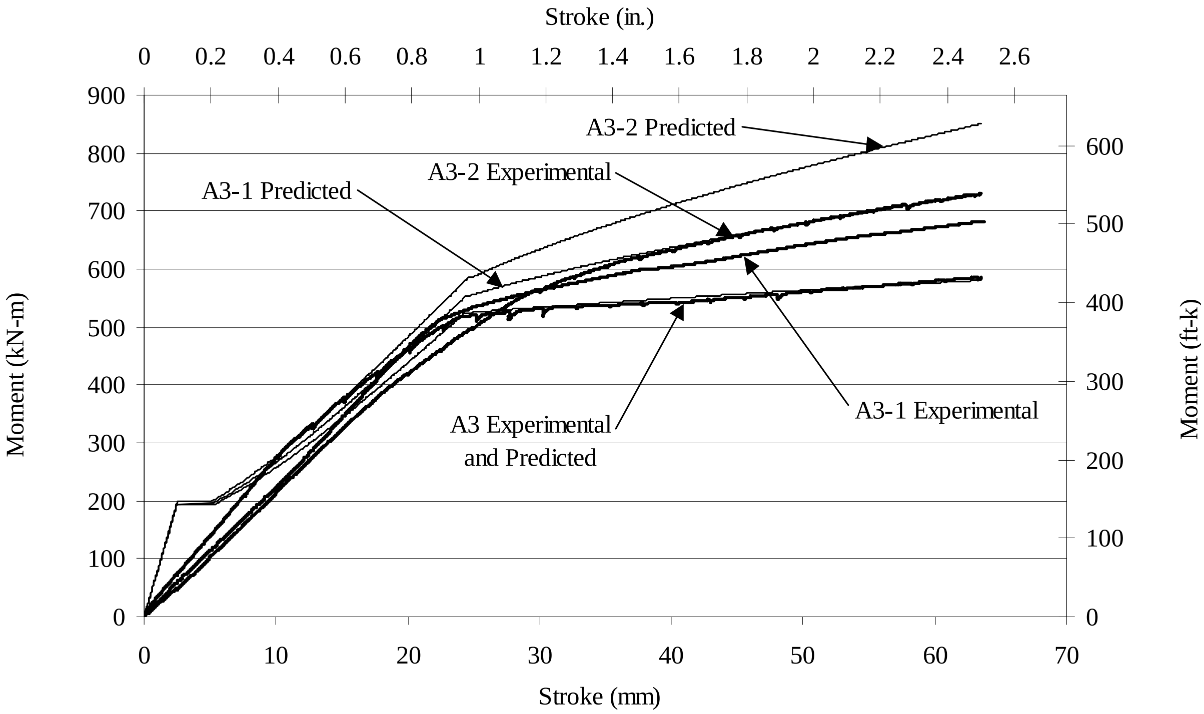

Figure 7. Experimental and predicted moment-stroke plots for A3 T beams.

In the uncracked region, it is clear that the analytical predictions are stiffer than the experimental curves. This is part in fact due to the cycling of the T beams before they were tested for this study. It can be seen in Figure 7 that the experimental and predicted moment-deflection curves are nearly identical for the unstrengthened control beam A3. The predicted curve is higher than the experimental curve for beams A3-1 and A3-2. After the yield point, the prediction for A3-1 is close to the experimental curve for beam A3-2. This leads us to believe that slip exists between the FRP strip and the concrete section. It should also be noted that the experimental curves are moment-stroke data, while the predicted curves are moment-deflection data.

Conclusions

It is possible to strengthen reinforced concrete T beams by attaching FRP strips with mechanical fasteners. The fastening procedure required no surface preparation. The beam strengthened with one strip showed an increase of 8.0 % in yield moment and 14.4 % in the moment at a mid span deflection of 63.5 mm (2.5 in.). The beam strengthened with two strips showed an increase of 11.7 % in yield moment, and an increase of 27.2 % in the ultimate moment. The analytical model provided calculated / experimental values around 1.09 for the yield moments, yield deflections, and moments at a mid span deflection of 63.5 mm (2.5 in.).

To further refine the analytical model, slip between the strip and the concrete is being considered, which will allow the model to predict the reduction in strengthening as the individual connections reach their maximum capacity. Fatigue testing will be conducted to determine the effect of cyclic loading on reinforced concrete beams strengthened using this method.

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Notation

a_f	Distance from the support to the end fasteners
c	Depth to the neutral axis
EA	Axial stiffness
F_{efu}	Ultimate strength of an end fastener
F_{fu}	Ultimate strength of a fastener
f_{frp}	Stress in the FRP strip
f_{yfrp}	Ultimate stress of the FRP strip
M_f	Applied moment at the location of the end fasteners
M_{mc}	Moment calculated with the moment-curvature model
P_{ef}	Force per end faster
P_f	Force per fastener
s_f	Spacing between the fasteners
T_{frp}	Force in the FRP strip
$T_{y,frp}$	Force in the FRP strip at the end fasteners
ε_c	Strain in the extreme compression fiber of the concrete
ε_i	Initial strain in the extreme compression fiber of the concrete
ε_{inc}	Increment in strain in the extreme compression fiber of the concrete
ϕ	curvature calculated with the moment-curvature model

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