Flexural Fatigue Behavior of Reinforced Concrete Beams Strengthened with FRP Fabric and Precured Laminate Systems

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Abstract: Rehabilitation of existing structures with carbon fiber reinforced polymers (CFRP) has been growing in popularity because they offer resistance to corrosion and a high stiffness-to-weight ratio. This paper presents the flexural strengthening of seven reinforced concrete (RC) beams with two FRP systems. Two beams were maintained as unstrengthened control samples. Three of the RC beams were strengthened with CFRP fabrics, whereas the remaining two were strengthened using FRP precured laminates. Glass fiber anchor spikes were applied in one of the CFRP fabric strengthened beams. One of the FRP precured laminate strengthened beams was bonded with epoxy adhesive and the other one was attached by using mechanical fasteners. Five of the beams were tested under fatigue loading for two million cycles. All of the beams survived fatigue testing. The results showed that use of anchor spikes in fabric strengthening increase ultimate strength, and mechanical fasteners can be an alternative to epoxy bonded precured laminate systems.

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Introduction

Fiber reinforced polymers (FRP) have gained importance in bridge rehabilitation in recent years. The main reason is their high stiffness-to-weight ratio over steel plates. Moreover, these materials are less affected by corrosive environmental conditions, known to provide longer life and require less maintenance.

A manual lay-up method using two-part epoxies is the conventional way to bond composite fabrics and precured laminates to concrete substrate. The main disadvantage of this method is the peeling stresses that may be induced at the location of cracks or ends of the fabric or precured laminates, stresses which tend to pull the strip away from the concrete. The peeling of carbon FRP (CFRP) composite may cause a sudden and catastrophic failure of the structure. Another disadvantage is the detachment of CFRP fabric due to the vertical displacement of concrete caused by shear cracking (ACI 2002b; Lopez et al. 2003). Manual lay-up may be labor intensive if it requires significant surface preparation.

End anchorage might prevent the premature peeling of CFRP fabrics from the concrete substrate. In fact, proper anchoring systems may help CFRP precured laminate to develop higher stresses throughout its length (Barnes and Mays 1999), decreasing stress concentrations and increasing bond strength. The use of spikes can increase the flexural capacity of strengthened beams by as much as 35% when compared to strengthened beams without anchor spikes (Eshwar et al. 2003). The same type of glass fiber anchor spikes were also applied on reinforced concrete (RC) slabs strengthened with a prestressing FRP system, preventing delamination (Yu et al. 2003).

A new system that has recently been developed at the Univ. of Wisconsin-Madison yielded successful results of FRP precured laminates attachment to concrete [mechanically fastened-fiber reinforced polymers (MF-FRP)] (Lamanna et al. 2001a,b,c; Ray et al. 2001a,b; Lamanna 2002; Borowicz 2002). The installation of the MF-FRP system has proven to be fast and easy, and requires unskilled labor with common hand tools. Moreover, the surface preparation can be reduced at the removal of sizeable protrusions such as form lines. The efficiency of this rapid-repair strengthening system was demonstrated by rehabilitating an existing bridge and testing two slabs cut from the structure up to failure (Borowicz et al. 2004). The slabs were strengthened with three and five MF-FRP precured laminates, and the ultimate flexural capacity was 25 and 45% higher than the ultimate flexural capacity of the unstrengthened slab, respectively. Failure was reached with compression crushing of the concrete for both specimens while the FRP precured laminates were still firmly attached. A similar method of strengthening was developed at the Univ. of Missouri-Rolla (UMR). In lieu of pins, concrete wedge bolts and anchors were used. The latter was found to be more effective since the presence of hard aggregates in the concrete could damage the thread of the bolts. Three off-system bridges in Phelps

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Table 1. Material Properties and Reinforcement Geometry

Material	Strength (MPa)	Modulus of elasticity (GPa)	Ultimate strain ($\mu\varepsilon$)	Thickness (mm)	Width (mm)	Cross-section area (mm^2)
Concrete[a]	27.6[b]	25.1[c]	3,000	NA	NA	NA
Reinforcing steel[d]	413.7[e]	200[e]	2,070	NA	NA	NA
CFRP fabric[d,f]	3792	227.5	16,670	0.165	203.2	33.5
CFRP precured laminate[d]	835[g]	62[g]	14,000	3.175	101.6	322.6

[a] Compressive properties.

[b] The compressive strength was determined at 28 days according to ASTM C 39-01 (2001).

[c] The modulus of elasticity in compression was determined at 28 days according to ASTM C 469-94 (1994).

[d] Tensile properties.

[e] The yield strength and the modulus of elasticity were determined according to ASTM A 370-02 (2002).

[f] Data obtained by the manufacturer.

[g] The stress at failure and the modulus of elasticity of the laminate were determined according to ASTM D 3039 (2006).

County, Mo., were strengthened using the MF-FRP system in 2004 (Rizzo 2005). Thus it was possible to compensate for an insufficient amount of longitudinal reinforcement, in this case the reason for which the entire superstructure elements were visibly cracked.

Another issue that should be addressed is the performance of these systems under fatigue loading. Even though the static behavior of various FRP application systems has been widely studied, fatigue resistance still requires further investigation. Composites are believed to have a higher resistance to fatigue compared to other engineering materials (Ekenel 2004). It has been reported that the fatigue durability of RC beams significantly improved after strengthening with externally bonded FRP laminates (Barnes and Mays 1999; Shahawy and Beitelman 1999; El-Tawil et al. 2001; Senthilnath et al. 2001; Papakonstantinou 2001; Brena et al. 2002). Previous researchers stated that the fatigue failure of RC beams is not always by the same mechanism as static failure (Barnes and Mays 1999). An improvement in fatigue life after strengthening with FRP laminates is expected as the increase in stiffness and strength reduces the crack propagation, causing a reduction of stress in the reinforcing steel. Grace (2004) applied a fatigue loading at service load levels for two million cycles on RC beams strengthened with CFRP precured laminate and fabric; no significant effect on the ultimate load-carrying capacity of such beams was observed.

This study investigates the affect of fatigue loading on flexural residual capacity of two different FRP strengthening techniques: CFRP fabric and precured laminates bonded with epoxy, and FRP precured laminates mounted with mechanical fasteners (MF). Glass fiber anchor spikes were used as a supplemental end anchorage for one of the CFRP fabric strengthened beams in order to investigate their efficiency under cyclic and static flexural loading.

Experimental Investigation

Material Properties

Table 1 summarizes the material properties for concrete, steel reinforcement, CFRP sheets, and precured laminates. It is noteworthy to mention that the CFRP sheet properties are fiber related, whereas the CFRP precured laminates properties are gross cross section related.

Analytical Design

The strength models used to predict the ultimate capacity of the critical section utilize strain compatibility in the section, equilibrium, and constitutive relations of the materials. Bonded CFRP fabrics and precured laminate were idealized as linear up until failure. In order to avoid cover delamination or FRP debonding, a limitation was placed on the strain level developed in the laminate using the bond-dependent coefficient for flexure (κ_m) according to ACI Committee 440.2R-02 (ACI 2002b). Table 2 summarizes the design stresses f_{fu} and strains ε_{fu}, the coefficient κ_m, the axial stiffness AE and the maximum force $A\kappa_m f_{fu}$ that can be developed by the strengthening of each beam according to ACI Committee 440.2R-02 (ACI 2002b). Coefficient κ_m was set equal to one for the beam strengthened with FRP fabrics using anchor spikes. In reality, the presence of the anchor spikes reduces the probability of having cover delamination or FRP debonding at the

Table 2. Parameters Used for Design

Strengthening description	f_{fu} (MPa)	ε_{fu} ($\mu\varepsilon$)	κ_m	AE (kN)	$A\kappa_m f_{fu}$ (kN)
CFRP fabric	3,385	14,880	0.893	7,633	114
CFRP fabric with anchor spikes	3,792	16,670	1.000	7,633	127
CFRP precured laminate with epoxy (bonded SafStrip)	460	7,345	0.551	20,190	148
CFRP precured laminate with wedge anchors (bolted SafStrip)	531	8,483	0.636	18,090	171

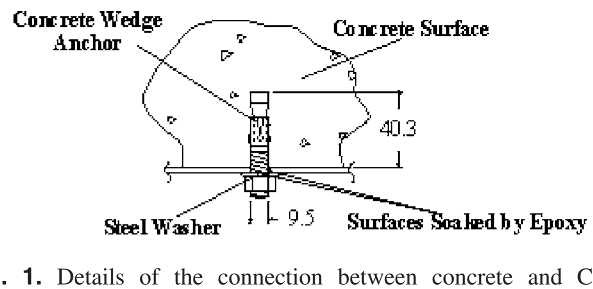

Fig. 1. Details of the connection between concrete and CFRP precured laminate with wedge anchors (mm)

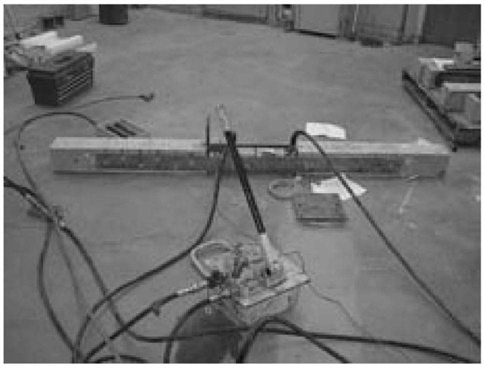

Fig. 2. Shear-bond test setup

ends of the fabric by absorbing part of the significant stress concentration (Eshwar et al. 2003; Smith and Teng 2001).

In order to simplify the calculation of the section properties by using the same model valid for bonded FRP systems, a different definition for the coefficient κ_m was introduced for FRP pre-cured connections to take into account the different mechanisms involved in the stress transferring process of this type of strengthening (such as net tension failure at open hole, concrete substrate failure, number and pattern of the fasteners, clamping pressure, concrete substrate failure, etc.). In addition, due to the particular behavior of the connection as described in the next paragraph, it was possible to estimate the coefficient $\kappa_{m,\text{bolted}}$ as

$$\kappa_{m,\text{bolted}} = \frac{1}{\varepsilon_{fu}} \frac{\min(F_{\text{FRP}}, n_{\text{fasteners}} \cdot P_{\text{bearing}})}{A_{\text{FRP}} E_{\text{FRP}}}$$

where ε_{fu}, A_{FRP}, and E_{FRP}=strain at failure of the laminate, the cross-section area, and modulus of elasticity, respectively; F_{FRP}=maximum allowable load in the laminate corresponding to the net section and $n_{\text{fasteners}}$ is the number of fasteners on one side of the beam; P_{bearing}=bearing capacity of the connection which takes the mode of failure of the connection into account depending on its geometrical details and clamping pressure. The previous expression of $\kappa_{m,\text{bolted}}$, valid for this particular MF-FRP system, needs to be reformulated and validated in further research works to obtain a more general formula.

Table 3. Beams Cross Section Properties

Strengthening description	Load at cracking (kN)	Load at yielding (kN)	Load at failure (kN)	Expected mode of failure
Unstrengthened	9.8	25.5	28.9	Compression
CFRP fabric	*	35.5	57.5	Compression
CFRP fabric with anchor spikes	*	35.5	57.5	Compression
CFRP precured laminate with epoxy (bonded SafStrip)	*	51.5	81.1	Tension (Peeling-delamination)
CFRP precured laminate with wedge anchors (bolted SafStrip)	*	51.5	82.3	Compression

Note: *=these beams were already cracked.

In order to mechanically fasten the FRP laminate to the concrete, the optimal solution in terms of mechanical behavior of the connection was determined as a result of an experimental program conducted at UMR (Rizzo 2005). The results of the bearing tests showed that the bearing capacity of the laminates is proportional to the diameter of the pin and the area restrained by the washer, which avoids the buckling of the fibers that are directly in contact with the pin. On the other hand, the bearing capacity can be reached only if the distance of the hole from the free edge is higher than 50.8 mm, thus preventing other failure modes such as shear-out or cleavage. The fastening system used in this experimental campaign can be seen in Fig. 1. The diameter of the pin was chosen to avoid the failure of the connection in the concrete substrate. The load that causes spalling of the concrete was calculated according to the ACI 355.1R-91 document (ACI 1991). The minimum embedment depth of the bolts was designed according to the recommendations provided by the manufacturer.

Single-bolted shear-bond tests (Fig. 2) were performed in order to obtain the ultimate shear capacity of the connection. It was observed that, for concrete having an f'_c=27.5 MPa, the failure mode was due to bearing of the FRP at 14.0 kN. Multibolted specimens were also tested to understand the stress distribution between the fasteners, and it was found that for the present CFRP

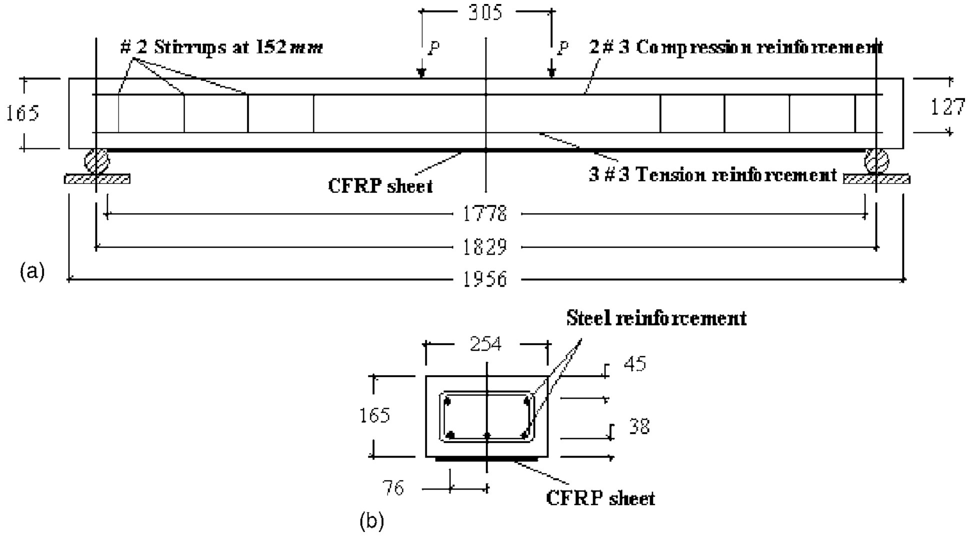

Fig. 3. Geometry of the specimens: (a) Longitudinal section (mm); (b) cross section (mm)

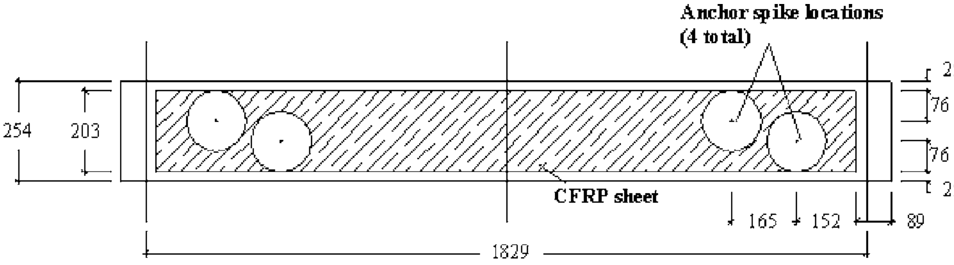

Fig. 4. Test plan for anchor spikes placement on beam (mm)

precured laminates, the applied load can be assumed as uniformly distributed between all the fasteners at the ultimate conditions (Rizzo 2005).

Therefore, for the specimen strengthened with MF-FRP system, 22 evenly spaced fasteners were used to attach the precured laminate in the shear spans in order to induce first concrete failure followed by the bearing failure at the connections. The spacing between the fasteners was chosen to satisfy the recommendations provided by ACI 355.1R-91 (ACI 1991) document and the manufacturer of the anchors.

Although the FRP precured laminate by itself is a linear elastic material, the MF-FRP precured laminate shows plastic behavior beyond the bearing strength P_b. In reality, it is possible to obtain a pseudoplastic behavior of the connection by using the proper geometrical details (edge distance, washer, gap filler, etc.). Herein, the term "plastic" is used in the sense that the maximum load reached in the connection is not abruptly followed by a drop but it can be maintained until large elongation of the hole. Therefore, the behavior of the MF-FRP connection was modeled as elastic-perfectly plastic.

The strain distribution across the section was calculated assuming that the strains in the reinforcement and concrete are directly proportional to the distance from the neutral axis, that is, a plane section before loading remains plane after loading. In the case of the MF-FRP precured laminate, this assumption is not completely accurate because there is not intimate contact between the concrete and external FRP reinforcement. This approach was used for convenience of calculation as an approximation to avoid the relative slip between the MF-FRP laminate and the concrete substrate due to the presence of gaps in the connection components, the elastic deformation of the bolts, and the bearing mechanisms corresponding to the holes' locations.

It is important to underline that the load distribution for the MF-FRP precured laminate under bending is complex. It is understood that bearing of the FRP precured laminate at the location of the fasteners introduces nonuniformity to the strain across the section. In the context of this work, a uniform distribution of stress across the section of FRP precured laminate was assumed as a simplification of the problem. This approach allows us to estimate the resultant tension force in the FRP strengthening as $A_{\mathrm{FRP}}E_{\mathrm{FRP}}\varepsilon_{\mathrm{FRP}}$, where A_{FRP}, E_{FRP}, and $\varepsilon_{\mathrm{FRP}}$ are the cross section, the modulus of elasticity, and the strain of the FRP laminate, respectively ($\varepsilon_{\mathrm{FRP}}$ is calculated in the previous assumption that plane cross sections before loading remain plane after loading) (Rizzo 2005).

Table 3 summarizes the design properties of the cross section for all the beams. The expected failure loads for the beams strengthened with bonded fabric sheets are the same because the expected modes of failure are crushing of the concrete for both of them even though the κ_m factors are different. It is also noteworthy to mention that the expected mode of failure for the beam with the bonded CFRP precured laminate is peeling-delamination; whereas the one strengthened with the MF-FRP system is compression.

Sample Preparation

Seven RC beams were fabricated in the laboratory for this investigation. The width and the height of the cross section are 254 and 165 mm, respectively. The total area and the effective depth of the tension side steel reinforcement are 214 mm^2 and 122 mm, respectively. The total area and the clear concrete cover of the compression side steel reinforcement are 142 mm^2 and 45 mm, respectively. The dimensions and cross-sectional details of the

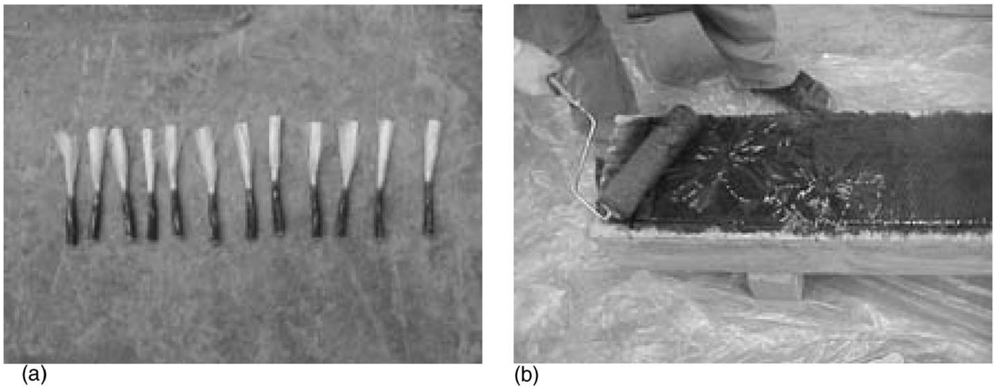
(a) (b)

Fig. 5. Beam strengthened with bonded CFRP fabrics and using anchor spikes: (a) Half saturated dry glass fibers; (b) final shape of anchor spikes

Fig. 6. Beam strengthened with bonded CFRP precured laminate (epoxy application)

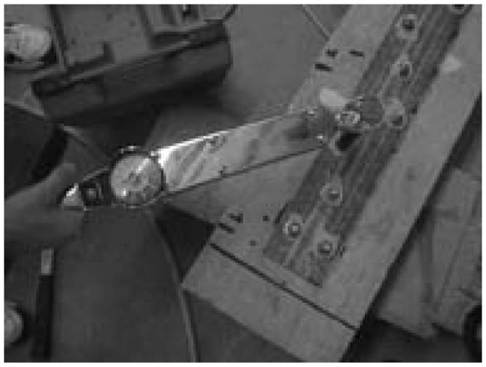

Fig. 7. Beam strengthened with mechanically fastened CFRP precured laminate

test beams are shown in Fig. 3. Two beams served as unstrengthened control specimens (S-0 and S-0F). Beam S-0 was tested under static loading while beam S-0F cycled under 2 million fatigue cycles prior to static testing (*F* represents fatigue cycling). All of the beams were precracked before strengthening by loading the beams beyond the cracking load to simulate the condition of a typical RC beam prior to repair/strengthening.

Three beams were strengthened with a single CFRP ply throughout the length of the tension face of test specimens (S-1, S-1F, and S-2F). Except cleaning by wire brushing and pressurized air, no other surface preparation method was applied in order to simulate a worse case situation for bond prior to cycling. The CFRP fabric was applied in approximately 45 min per beam. The curing time of epoxy was 48 h (under laboratory conditions) as recommended by manufacturer.

Four anchor spikes were applied on one of the CFRP fabric strengthened beams (Beam S-2F). The anchors were located at the ends of the sheet, where high peeling and shear stresses may develop. The purpose was to prevent the premature peeling of CFRP laminates by anchoring CFRP fabrics to the concrete. The locations were determined based on the information obtained from the previous studies done by Sagawa et al. (2000), Eshwar et al. (2003), and Yu et al. (2003). The strengthening plan is illustrated in Fig. 4. Spikes were formed from dry glass fibers, and they were half dry and half coated with epoxy. Glass fibers were preferred because of their economical advantages. The epoxy-coated part had a diameter of approx 9.5±1.5 mm [see Fig. 5(a)]. First, four holes were drilled into the concrete with the dimensions of 25.4 mm in depth and 12.7 mm in diameter. Then, primer was applied on the tension side of the beam, which was followed by the application of saturant. The holes were also filled with saturant to the half of their depths. After applying the CFRP fabric, the precured part of the anchor spikes was inserted into the holes throughout the fabric. The dry fibers were fanned out over the CFRP fabric. Finally, a second layer of saturant was applied and roller spikes used to avoid any air bubbles at the interface [Fig. 5(b)]. The system was cured for 48 h in laboratory environment according to manufacturer's recommendation.

Two of the beams were strengthened using CFRP precured laminates (S-3F and S-4F). For beam S-3F, the precured laminate was bonded over the tension zone of the concrete using epoxy. The epoxy was laid on the concrete with a thickness of 3.2 mm (see Fig. 6). Finally the CFRP precured laminate was placed over epoxy and pressure was applied by a spike roller to force air bubbles out. The application was done in approximately 15 min/beam. For Beam S-4F, the precured laminate was mechanically fastened to the concrete surface by means of concrete wedge anchors with 9.5 mm diameter and 57.1 mm total length. First, holes were drilled according to the design pattern into the concrete to a depth of 50.8 mm using a 9.525 mm diameter solid carbide-tipped bit. The precured laminate was drilled using the same bit and pattern of holes, cleaned of dust, and laid on the concrete surface. Finally, the fasteners were hammered into the holes over the CFRP precured laminate making sure that the nut and the washer were resting solidly against the fixture. The steel washer had an 11.1 mm inner diameter, a 25.4 mm outer diameter, and a 20.6 mm thickness. At this point, the gaps between anchors and FRP were filled with epoxy in a way that the amount of resin was enough to wet the washer-FRP interface. In this fashion, the rigid movement of the anchors was not prevented as the gaps between the fasteners and the concrete sleeve were not filled. Finally, the nuts were tightened with a wrench to a torque in the range of 34.0–41.0 N m (Fig. 7) according to the manufacturer's specifications in order to limit the shear stress due to the torsion on the anchor. The application took about one hour. The test plan is presented in Fig. 8.

Test Setup and Procedure

Beams S-0F, S-1F, S-2F, and S-4F were tested for fatigue over a simply supported span of 1,829 mm. The beams were loaded with two concentrated loads placed at equal distance (152 mm) from the beam centerline. The supports were placed 63 mm away from the end points. A sketch of the test setup is shown in Fig. 3(a). All five beams were cycled under fatigue loading between a minimum of 33% and a maximum of 63% of the theoretical ultimate flexural capacity of the section. These load percentages were extrapolated based on the safety factors proposed by AASHTO (2000) which were simulated common service conditions that a structure, like a bridge, might experience during its lifetime. Table 4 shows the applied minimum and maximum loads for each beam. Subjecting the beams to the same percentage of the ultimate moment capacity seemed an appropriate method to compare fatigue performance of fabrics strengthened and precured laminate strengthened beams with different capacity. Because the maximum load of Beams S-3F and S-4F exceed the yielding loads presented at Table 3, it is noteworthy to mention that the values in Table 3 are theoretical calculations. The tests were terminated either when the beam failed or reached 2 million cycles, whichever occurred first. The frequency applied during the fatigue testing was 2 cycles/s (2 Hz).

Prior to actual fatigue testing, a ten-cycle test was performed

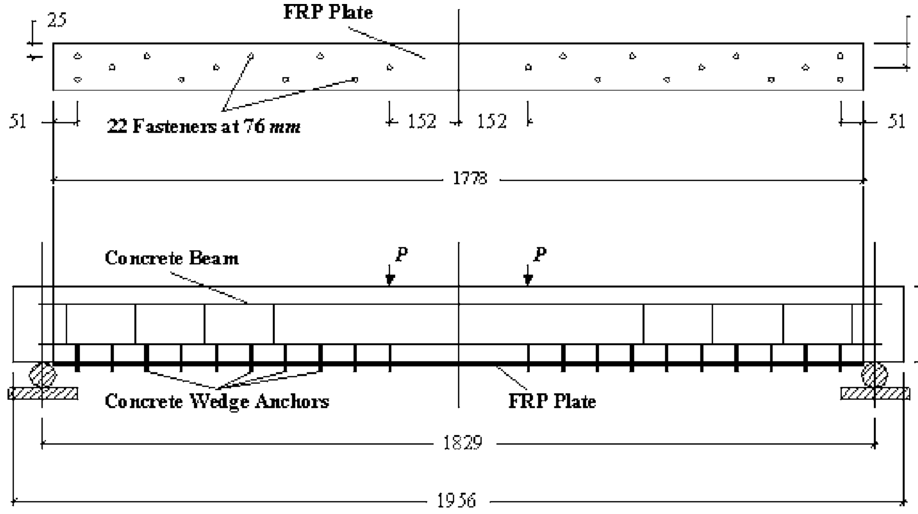

Fig. 8. Concrete wedge anchors pattern (mm)

to measure the mid-span displacement of the beams by using linear variable differential transducer (LVDT). The frequency was adjusted to 0.1 Hz during this ten-cycle test in order to capture adequate number of data points. The same tests were performed during the fatigue testing after every 0.5, 1, 1.5, and 2 million cycles and the corresponding stiffness was determined.

Experimental Results

Fatigue Test Results

All beams survived 2 million cycles. The initial and 2 million cycle stiffness measurements for the unstrengthened control sample (S-0F) were 7.46 and 6.30 kN/mm, respectively (see Fig. 9). This corresponds to a decrease of 16% at 2 million cycles as compared to initial cycle. The stiffness mentioned herein is defined as the slope of the load versus midspan displacement relation between the maximum and minimum specified loads.

Fig. 9 shows the measured stiffness versus number of cycles. Fig. 10 shows the midspan deflections versus number of cycles. As shown in Fig. 9, it was observed that most of the stiffness loss occurred between first and 0.5 million cycles. The phenomenon is related to the opening and propagation of the cracks, which implies a relative slip between concrete, steel reinforcement, and the FRP strengthening (local microdebonding at the tips of the cracks in the case of bonded systems, partial rotation of the fasteners, relative slip between the components of the connections due to the presence of gaps and local microcrushing of the concrete in the contact area in the case of bolted system) as well as failure of

Table 4. Fatigue Test Program

Beam number	Strengthening description	Minimum and maximum load Applied (kN)
S-0F	Unstrengthened	9.8–18.7
S-1F	CFRP fabric	17.3–33.4
S-2F	CFRP fabric with anchor spikes	17.3–33.4
S-3F	CFRP precured laminate with epoxy	28.9–55.2
S-4F	CFRP precured laminate with wedge anchors	28.9–55.2

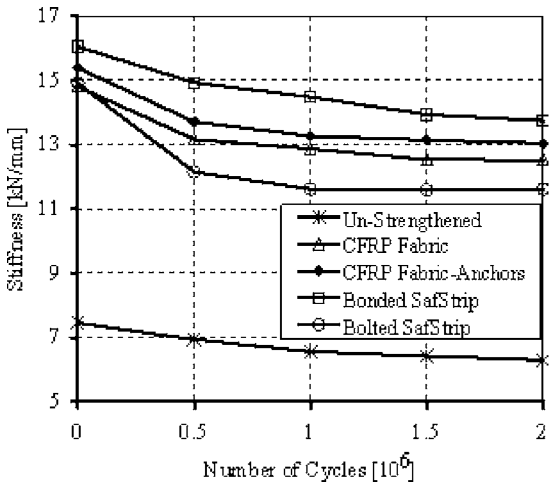

Fig. 9. Stiffness versus number of cycles

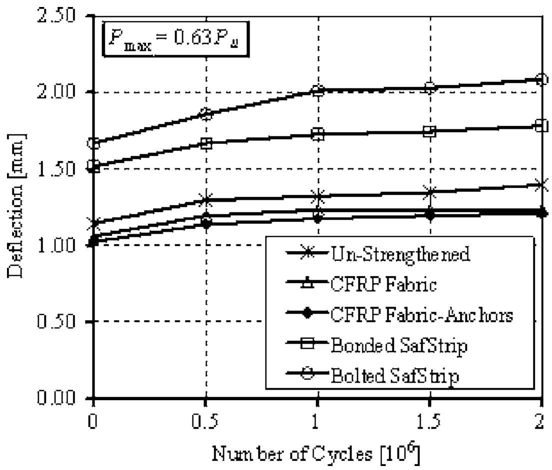

Fig. 10. Maximum deflections versus number of cycles

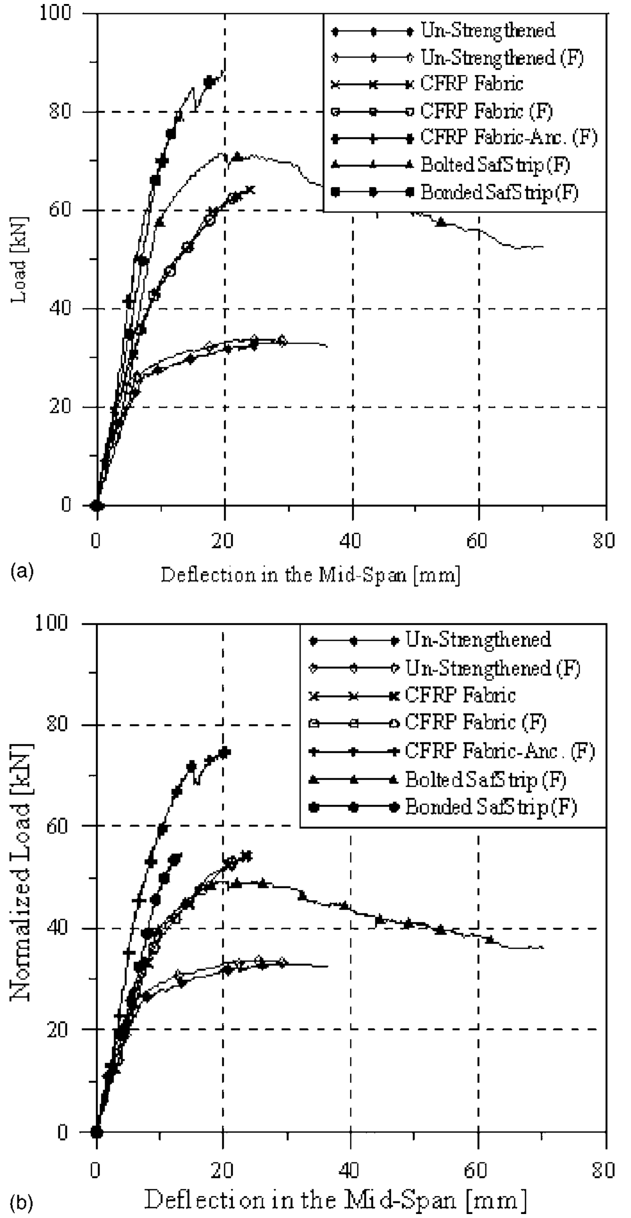

Fig. 11. Load versus midspan displacement curves until test beams failure (F=fatigued prior to static test): (a) Raw data; (b) normalized data

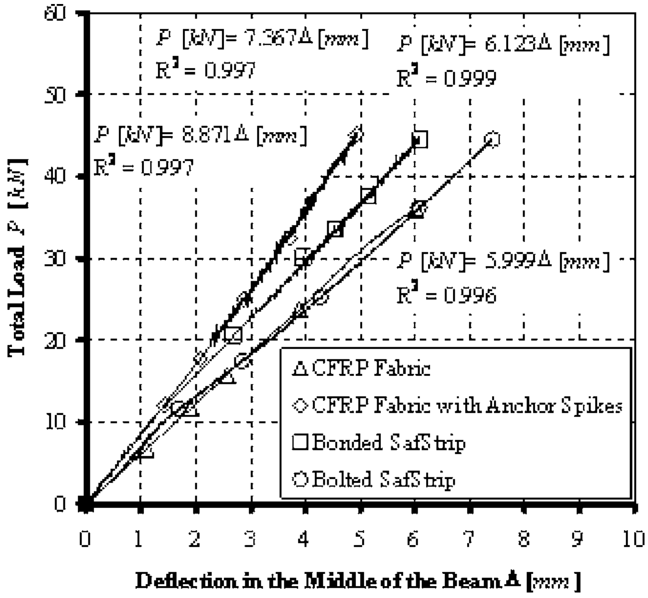

Fig. 12. Load versus midspan curves up to proportional limit for all fatigued beams

the concrete in the tensile zone (not accounted in conventional calculations). After 1 million cycles, all the previous microfailures reduced. The interlocking of the steel bars (due to the ribs on the surface) avoided further relative slip at the interface steel concrete; the debonding zones and cracks in the concrete stabilized and the fasteners were fixed in a stable position. The highest change in stiffness was observed in CFRP pre-cured laminate strengthening with mechanical fasteners (S-4F) by 22% at 2 million cycles as compared to initial cycle. All others (S-1F, S-2F, and S-3F) showed a decrease of 15% on average at 2 million cycles.

Flexural Test Results

All seven beams were tested under flexural loading. The flexural tests were performed under four point bending and mid-span displacements were recorded using LVDT. Fig. 11(a) exhibits the load versus midspan displacement diagrams of test beams loaded until failure. As shown in Fig. 11(a), Beam S-2F exhibited a 39% higher capacity as compared to Beam S-1. The increase in capacity can be attributed to the presence of the anchor spikes that improved the bond properties at the concrete-CFRP interface.

Table 5. Expected and Measured Failure Loads

Beam number	Strengthening description	$\frac{E_sA_s+E_fA_f}{E_sA_s}$	Failure load Expected (kN)	Measured (kN)	Normalized[a] (kN)
S-0	Unstrengthened	1.000	28.9	33.0	33.0
S-0F	Unstrengthened	1.000	28.9	33.4	33.4
S-1	CFRP fabric	1.179	57.5	64.1	54.4
S-1F	CFRP fabric	1.179	57.5	63.2	53.6
S-2F	CFRP fabric with anchor spikes	1.179	57.5	89.5	75.9
S-3F	CFRP precured laminate with epoxy	1.449	81.1	80.4	55.5
S-4F	CFRP precured laminate with wedge anchors	1.449	82.3	71.1	49.1

[a] Measured failure load/expected failure load.

Fig. 13. Modes of failure of the specimens: (a) Unstrengthened control sample; (b) CFRP fabric; (c) CFRP fabric with anchor spikes; (d) bonded FRP precured laminate (bonded SafStrip); (e) MF-FRP system (bolted SafStrip)

This can be seen in the failure modes between S-1 and S-2F. S-1 failed by complete CFRP debonding; whereas, anchor spikes were still holding until S-2F failed by delamination/fracture of fabric.

Table 5 compares the expected and the measured failure loads. The measured loads were also normalized in order to provide a fair analysis between the different strengthening techniques [see Fig. 11(b)]. The normalization was performed by dividing the measured loads by a stiffness coefficient, defined as the ratio between the total tension strengthening (CFRP+steel) stiffness and the steel reinforcement one. As shown in Table 5, the average increase in ultimate failure load by single-ply CFRP strengthening as compared to unstrengthened beam was 94%. Beams S-2F and S-3F exhibited failure loads which were 39 and 2% higher than S-1, respectively; however, S-4F showed a failure load which was 10% lower than S-1.

The relative slip between concrete and precured laminate that might occur in the case of the beam strengthened using the MF-FRP system (S-4F) explains the lower value of strength found as compared with the beams strengthened with the bonded system. In reality, the engagement between fasteners and FRP precured laminate was complete after steel yielded. This phenomenon allowed for a larger magnitude of crack propagation. The effect can be attributed to the accumulation of the damages at the location of the fasteners. In fact, due to the particular pattern of the fasteners and loading configuration, six anchors in the midspan of the specimen (three for each side) experienced a load higher than the average load at bearing of the single connection during the fatigue cycles. Consequently, the effective fasteners that anchored the laminate were only 16, not 22. Recalculating with only 16 fasteners, the ultimate load at failure results 74.8 kN, value very close to the experimental one (71.1 kN). This conclusion underlines the importance to check the connections of a MF-FRP fastening system for both ultimate and service load conditions (Rizzo 2005). Occasional overloads can highly affect the performance of the strengthening at ultimate condition.

A decrease in ductility due to fatigue cycling can also be seen in Fig. 11. Beams S-0F and S-1F displayed midspan deflections which were 13 and 18% lower than S-0 and S-1, respectively. However, there was no decrease in ultimate strength. The decrease in ductility can be explained by the higher crack formation due to the fatigue cycles.

Fig. 12 shows the load versus midspan displacement curves of fatigued beams up to the proportional limit. As illustrated, the slopes of the load-deflection curves measured in static loading (see Fig. 12) are lower than the ones measured in fatigue loading (see Fig. 9). This can be speculated as the hysteresis effect which caused the RC beam to start a successive cycle before being fully recovered from the previous one; however, this parameter can be used for comparison purposes among each representative specimen. As shown in Fig. 12, Beams S-2F, S-3F, and S-4F exhibited slopes which were 48, 22, and 3% higher than S-1, respectively.

Fig. 13 shows the failure modes of the test samples. Both unstrengthened control samples (S-0 and S-0F) failed by concrete crushing. The CFRP fabric applied samples (S-1 and S-1F) failed by concrete crushing followed by a complete CFRP delamination. As a consequence of the extended cracking phenomena, CFRP fabric was detached and torn off [see Fig. 13(b)]. The failure mode of Beam S-2F was crushing of the concrete. Analyzing the specimen after failure, it was possible to detect that the failure mode of Beam S-2F was crushing of the concrete, followed by delamination of the CFRP fabric at the midsection; consequently, breaking on one side close to the anchor spikes. Both beams strengthened with CFRP fabrics exhibited very similar midspan displacement readings at failure load and both failures were instant and catastrophic. The beam strengthened with FRP precured laminate bonded with epoxy (S-3F) failed at a load of 13% higher than the beam strengthened with MF-FRP system (S-4F). The failure of the Beam S-3F was catastrophic. After the compression crushing of the concrete, the precured laminate peeled off at one side of the beam [see Fig. 13(d)]. On the other hand, the failure of the Beam S-4F was very ductile; the pre-cured laminate was firmly attached at the surface of the concrete until very large deflections occurred with rotation of the majority of fasteners [see Fig. 13(e)]. After the test, the beam was rolled upside down allowing the detection of extensive bearing failure at the locations of the fasteners.

Conclusions

The following conclusions can be drawn based on the fatigue and flexural tests results presented in this paper:

- The FRP strengthening increased the fatigue life of RC beams by increasing stiffness and reducing crack propagation;
- The change in stiffness at 2 million cycles as compared to initial cycle was approximately the same for all the beams (15%) except Beam S-4F (22%). This is due to the fasteners which allowed greater crack formation and propagation until the complete engagement of the strengthening;
- The fatigue loading slightly reduced the members' ductility but did not significantly affect the failure load for the CFRP fabric strengthened and unstrengthened specimens tested;
- Based on the flexural test results, it can be concluded that the analytical design using ACI Committee 440.2R-02 (ACI 2002b) was conservative in calculating the ultimate capacity of the beam even after 2 million fatigue-cycling at service load, except for the beam strengthened with mechanically fastened FRP precured laminate which showed a load at failure 14% lower than the expected value. This can be partially attributed to the higher damage accumulation in the FRP precured laminate around the anchorage holes. Monitoring the damage accumulation in cyclic loading would be interesting for future investigation;
- The fatigue and static loading exhibited that the use of mechanical fasteners can be an alternative to the epoxy bonded systems. Moreover, the beam strengthened with MF-FRP showed a more desirable apparent ductile behavior as compared to the beam strengthened with epoxy bonded FRP system. The increase in ductility exhibited by Beam S-4F was 3.5 times that of Beam S-3F;
- The use of anchor spikes (S-2F) resulted in a significant increase (39%) in the ultimate capacity of the beam as compared to CFRP strengthened beam without anchor spikes (S-1). The increase in capacity can be attributed to the presence of the anchor spikes that improved the bond properties at the concrete-CFRP interface, which can be seen in the failure modes of Beams S-1 and S-2F. The increase in labor costs using this anchorage technique could be offset by a reduction in the flexural reinforcement used.

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References

American Association of State Highway and Transportation Officials (AASHTO). (2002). *Standard specifications for highway bridges*, 17th Ed., Washington, D.C.

American Concrete Institute (ACI). (1991). "State-of-the-art report on anchorage to concrete." ACI Committee 355.IR-91, Detroit.

American Concrete Institute (ACI). (2002b). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures." ACI Committee 440.2R-02, Farmington Hills, Mich.

ASTM. (1994). "Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression." ASTM C 469, Vol. 04-02, Philadelphia.

ASTM. (2001). "Standard test method for compressive strength of cylindrical concrete specimens." ASTM C 39, Vol. 04-02, Philadelphia.

ASTM. (2002). "Standard test methods and definitions for mechanical testing of steel products." ASTM A 370, Vol. 04-02, Philadelphia.

ASTM. (2006). "Standard test method for tensile properties of polymer matrix composite materials." ASTM D 3039, Vol. 15-02, Philadelphia.

Barnes, R. A., and Mays, G. C. (1999). "Fatigue performance of concrete beams strengthened with CFRP plates." *J. Compos. Constr.*, 3(2), 63–72.

Borowicz, D. T. (2002). "Rapid strengthening of concrete beams with powder actuated fasteners and fiber reinforced polymer (FRP) composite materials," M.S. thesis, Univ. of Wisconsin–Madison, Madison, Wis.

Borowicz, D. T., Bank, L. C., Nanni, A., Arora, D., Deza, U., and Rizzo, A. (2004). "Ultimate load testing and performance of bridge strengthened with fiber reinforced composite materials and powder-actuated fasteners." *Proc., 83rd Annual Transportation Research Board Meeting* (CD-ROM), Washington, D.C.

Brena, S. F., Wood, S. L., and Kreger, M. E. (2002). "Fatigue tests of reinforced concrete beams strengthened using carbon fiber reinforced polymer composites." *Proc., 2nd Int. Conf. on Durability of FRP Composites for Construction*, Montreal, Quebec, 575–586.

Ekenel, M. (2004). "Durability performance of advanced construction materials used in infrastructure repair and rehabilitation systems." Ph.D. dissertation, Univ. of Missouri-Rolla, Rolla, Mo.

El-Tawil, S., Ogunc, C., Okeil, A., and Shahawy, M. (2001). "Static and fatigue analyses of RC beams strengthened with CFRP laminates." *J. Compos. Constr.*, 5(4), 258–267.

Eshwar, N., Ibell, T., and Nanni, A. (2003). "CFRP strengthening of concrete bridges with curved soffits." *Proc., Int. Conf. on Structural Faults and Repairs*, Montreal, Quebec.

Grace, N. F. (2004). "Concrete repair with CFRP." *Concr. Int.*, 26(5), 45–52.

Lamanna, A. J. (2002). "Flexural strengthening of reinforced concrete beams with mechanically fastened fiber—reinforced polymer strips." Ph.D. thesis, Univ. of Wisconsin-Madison, Madison, Wis.

Lamanna, A. J., Bank, L. C., and Scott, D. W. (2001a). "Flexural strengthening of RC beams using fasteners and FRP strips." *ACI Struct. J.*, 98(3), 368–376.

Lamanna, A. J., Bank, L. C., and Scott, D. W. (2001b). "Rapid flexural strengthening of RC beams using powder actuated fasteners and FRP strips." *Proc., FRPRCS-5 Fiber Reinforced Plastics for Reinforced Concrete Structures*, Vol. 1, Univ. of Cambridge, Cambridge, U.K., 389–397.

Lamanna, A. J., Bank, L. C., and Scott, D. W. (2001c). "Rapid strengthening of RC beams using powder actuated fasteners and FRP strips." *Proc., 5th Int. Symp. of FRP in Reinforced Concrete Structures*, Cambridge, U.K., 389–397.

Lopez, M. M., Naaman, A. E., Pinkerton, L., and Till, R. D. (2003). "Behavior of RC beams strengthened with FRP laminates and tested under cyclic loading at low temperature." *Int. J. Mater. Prod. Technol.*, 19(1–2), 108–117.

Papakonstantinou, C. G., Petrou, M. F., and Harries, K. A. (2001). "Fatigue behavior of RC beams strengthened with GFRP sheets." *J. Compos. Constr.*, 5(4), 246–253.

Ray, J. C., Scott, D. W., Lamanna, A. J., and Bank, L. C. (2001a). "Flexural behavior of reinforced concrete members strengthened using mechanically fastened fiber reinforced polymer plates." *Proc., U.S. Army Science Conf.*, Baltimore.

Ray, J. C., Velazquez, G. I., Lamanna, A. J., and Bank, L. C. (2001b). "Rapidly installed fiber-reinforced polymer (FRP) plates for upgrade of reinforced concrete bridges." *High Performance Materials in Bridges and Buildings*, Koha, Hawaii.

Rizzo, A. (2005). "Application in off-system bridges of mechanically fastened FRP (MF-FRP) procured laminates." M.Sc. thesis, Univ. of Missouri-Rolla, Rolla, Mo.

Sagawa, Y., Matsushita, H., Takeo, K., and Saito, M. (2000). "A study on a method of anchorage of carbon sheet for flexural strengthening." *Trans. Jpn. Concr. Inst.*, 22, 237–242.

Senthilnath, P. S., Belarbi, A., and Myers, J. J. (2001). "Performance of CFRP strengthened RC beams in the presence of delaminations and lap splices under fatigue loading." *Proc., Composites in Construction: 2001 Int. Conf.*, Porto, Portugal.

Shahawy, M., and Beitelman, T. E. (1999). "Static and fatigue performance of RC beams strengthened with CFRP laminates." *J. Struct. Eng.*, 125(6), 613–621.

Smith, S. T., and Teng, J. G. (2001). "Interfacial stresses in plated beams." *Eng. Struct.*, 23, 857–871.

Yu, P., Silva, P. F., and Nanni, A. (2003). "Flexural strengthening of concrete slabs by a three-stage prestressing FRP system enhanced with presence of GFRP anchor spikes." *Proc., Composites in Construction Int. Conf.*, Rende (CS), Italy.