EFFECT OF FATIGUE LOADING ON FLEXURAL PERFORMANCE OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH FRP FABRIC AND PRE-CURED 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 superior performance in terms of resistance to corrosion and high stiffness-to-weight ratio. This paper presents the flexural strengthening of five reinforced concrete (RC) beams with FRP. The analytical method and application details are also presented. One beam was maintained as an un-strengthened control sample. Two of the RC beams were strengthened with CFRP fabrics, whereas the remaining two were strengthened using FRP pre-cured laminates. Glass fiber anchor spikes were applied in one of the CFRP fabric strengthened beams. One of the FRP pre-cured laminate strengthened beams was bonded with epoxy adhesive and the other one was attached by using mechanical fasteners. All of the beams were tested under fatigue loading for 2-million cycles. All of the beams survived fatigue testing except for the un-strengthened control beam. The results showed that use of anchor spikes in fabric strengthening increase ultimate strength, and mechanical fasteners can be an alternative to epoxy bonded pre-cured laminate systems.

1. 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. Manual lay-up method using two-part epoxies is the conventional way to bond composite fabrics and pre-cured laminates to concrete substrate. The main disadvantage of this method is the peeling stresses that may be induced at the ends of the fabric or pre-cured laminates, stresses which tend to pull the strip away from the concrete. Another disadvantage is the detachment of CFRP fabric due to the vertical displacement of concrete caused by shear cracking [1 and 2]. The peeling of CFRP composite may cause a sudden and catastrophic failure of the structure. This procedure is also accepted to be labor intensive because it requires a significant surface preparation. One way to prevent the premature peeling of CFRP fabrics from the concrete substrate is by using end anchorage. In fact, proper anchoring systems may help CFRP pre-cured laminates develop higher stresses throughout their length [3]. Based on research conducted at the University of Missouri-Rolla (UMR), the use of spikes increased the flexural capacity of strengthened beams by as much as 35% when compared to strengthened beams without anchor spikes [4]. This study indicated that the anchors decreased stress concentrations and increased bond strength.

A new system that has recently been developed at University of Wisconsin-Madison (UW) yielded successful results of FRP pre-cured laminates attachment to concrete (Mechanically Fastened - Fiber Reinforced Polymers, MF-FRP) [5 and 6]. The installation of the MF-FRP system has proven to be fast and easy, and requires unskilled labor with common hand tools. Unlike the conventional method in which pre-cured laminate is attached by two-part epoxies, this method does not require use of epoxy and 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 structure by UW & UMR in 2003 [5]. A similar method of strengthening was developed at 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. In 2004, three off-system bridges in Phelps County - MO were strengthened using the MF-FRP system [7]. Using this system, it was possible to compensate for an insufficient amount of longitudinal reinforcement, which was the reason for the deficiency in these bridges. Increasing the load capacity of these bridges would allow for either the load posting removal or an increase in the posted restriction rating.

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. It has been reported that the fatigue durability of RC beams significantly improved after strengthening with externally bonded FRP laminates [3, 8, 9, 10 and 11]. 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. Previous researchers stated that the fatigue failure of RC beams is mostly caused by fatigue of reinforcement. Cracks in an un-strengthened member propagated upwards as the number of cycles progressed. This causes an increase in reinforcing steel stress until yield of the steel and therefore failure of the system was attained. CFRP strengthening decreases the stress concentrations at the flexural cracks in the concrete. This causes a greater number of cracks with reduced crack widths, which were bridged to each other by CFRP external reinforcement; therefore extending the fatigue life of the steel in the beam [3, and 10].

2. RESEARCH OBJECTIVES

This paper investigates the fatigue durability and flexural strength of two different FRP strengthening techniques: bonded CFRP fabric and pre-cured laminates with epoxy and mounted FRP pre-cured laminates with mechanical fasteners. Glass fiber anchor spikes were also used as a supplemental end anchorage for one of the CFRP fabric strengthened.

3. MATERIAL PROPERTIES

Table 1 summarizes the material properties for concrete, steel reinforcement, CFRP sheets and pre-cured laminates. It is noteworthy to mention that the CFRP sheets properties are fiber related, whereas the CFRP pre-cured laminates properties are cross section related. The compressive strength was determined at 28 days according to ASTM C 39-01 [12]. The modulus of elasticity in compression was determined at 28 days according to ASTM C 469-94 [12]. The yield strength and the modulus of elasticity of steel were determined according to ASTM A 370-02 [12]. CFRP material properties were obtained from manufacturer [12].

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Ultimate Strain</th>
<th>Thickness (mm)</th>
<th>Width (mm)</th>
<th>Cross Section Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>27.5</td>
<td>25.8</td>
<td>3000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reinforcing Steel</td>
<td>413</td>
<td>200</td>
<td>2065</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CFRP Fabric</td>
<td>3800</td>
<td>227.5</td>
<td>16667</td>
<td>0.165</td>
<td>203</td>
<td>33.55</td>
</tr>
<tr>
<td>CFRP Laminate</td>
<td>835</td>
<td>62</td>
<td>14000</td>
<td>3.175</td>
<td>102</td>
<td>322.58</td>
</tr>
</tbody>
</table>

4. ANALYTICAL DESIGN

In order to select the parameters of the cyclic load, it was necessary to estimate the load at failure of the specimens. 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 pre-cured 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 knocked down factor $K_m$ according to ACI Committee 440.2R-02. The coefficient $K_m$ was set equal to one for the beam strengthened with FRP fabrics using anchor
spikes. The presence of the anchor spikes reduced the probability of cover delamination or FRP debonding at the ends of the fabric. The strengthening with mechanically fastened FRP pre-cured laminate is not a bond critical application as specified in the ACI 440.2R-02 document. A different definition for the coefficient $K_m$ should be introduced to take into account the different mechanisms involved in the stress transferring process of this type of strengthening (net tension failure at open hole, concrete substrate failure, number and pattern of the fasteners… etc). In this way, the calculation of the section properties can be developed using the same model valid for a bonded FRP system. In order to mechanically fasten the FRP laminate to the concrete, the optimal solution in terms of mechanical behavior of the connection was determined based on an experimental program conducted at UMR [7].

For the specimen strengthened with the MF-FRP system, a total amount of 22 evenly spaced fasteners was selected in the shear spans in order to induce concrete failure initially followed by the bearing failure at the connections. 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 pre-cured laminate, this assumption is not completely accurate because there is not intimate contact between the concrete and external FRP reinforcement; this approach was taken for convenience of calculation as an approximation. Table 2 summarizes the design properties of the cross section for all the beams. The expected failure loads for the beams strengthened with the bonded fabric sheets are the same because the expected modes of failure are crushing of the concrete for both of them even though the $K_m$ factors are different. It is also noteworthy to mention that the expected modes of failure for CFRP pre-cured laminate with epoxy and with wedge anchors are peeling-delamination and compression, respectively.

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>Strengthening Description</th>
<th>$K_m$</th>
<th>Load at Cracking [kN]</th>
<th>Load at Yielding [kN]</th>
<th>Load at Failure [kN]</th>
<th>Expected Mode of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-0</td>
<td>Un-strengthened</td>
<td>-</td>
<td>9.8</td>
<td>25.5</td>
<td>28.9</td>
<td>Compression</td>
</tr>
<tr>
<td>S-1</td>
<td>CFRP fabric</td>
<td>0.893</td>
<td>35.5</td>
<td>57.5</td>
<td>Compression</td>
<td></td>
</tr>
<tr>
<td>S-2</td>
<td>CFRP fabric with anchor spikes</td>
<td>1.000</td>
<td>35.5</td>
<td>57.5</td>
<td>Compression</td>
<td></td>
</tr>
<tr>
<td>S-3</td>
<td>CFRP pre-cured laminate with epoxy</td>
<td>0.551</td>
<td>51.5</td>
<td>81.1</td>
<td>Tension (Peeling-Delamination)</td>
<td></td>
</tr>
<tr>
<td>S-4</td>
<td>CFRP pre-cured laminate with wedge anchors</td>
<td>0.572</td>
<td>51.5</td>
<td>82.3</td>
<td>Compression</td>
<td></td>
</tr>
</tbody>
</table>

* Beam was pre-cracked prior to strengthening.

5. SAMPLE PREPARATION

Five RC beams were fabricated in the laboratory for this investigation. The beams were designed to fail in flexural. The dimensions and cross-sectional details of the test beams are shown in Figure 1. One beam served as an un-strengthened control specimen. Two beams were strengthened with CFRP fabrics. The CFRP fabric was 203 mm wide and 0.1651 mm thick and applied as single ply throughout the length of the test span. The dimensions of CFRP fabric were chosen to result in a failure mode of yielding of reinforcement in tension followed by the crushing of the concrete without the rupture of the CFRP fabric. The same criterion was used in the design of RC beams strengthened with pre-cured laminates. All of the beams were pre-cracked before strengthening by loading the beams beyond the cracking load to simulate the condition of a typical RC beam prior to repair/strengthening.
Four anchor spikes were applied on one of the CFRP fabric strengthened beam (beam S-2). The anchors were located 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 strengthening plan is illustrated in Figure 2. Spikes were formed from dry glass fibers, half coated with epoxy. The epoxy-coated part had a diameter of approximately 9.5 ± 1.5 mm. After applying the CFRP fabric, the pre-cured part of the anchor spikes was inserted into the predrilled holes (prior to spike placement) throughout the fabric (see Figure 3). The dry fibers were fanned out over the CFRP fabric. A second layer of saturant was applied and roller spikes used to avoid any air bubbles at the interface. Two of the beams were strengthened using CFRP pre-cured laminates. For beam S-3, the pre-cured laminate was bonded over the tension zone of the concrete using epoxy. The CFRP pre-cured laminate was placed over epoxy and pressure was applied by a roller spike to force any air bubbles out.

For beam S-4, the pre-cured 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 (see Figure 4). First, the 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 pre-cured 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 pre-cured laminate making sure that the nut and the washer were resting solidly against the fixture. The steel washer had 11.1 mm inner diameter, 25.4 mm outer diameter and 20.6 mm thickness. The gaps between anchors and FRP were filled with epoxy in a way that the amount of resin was sufficient to wet the interface washer-
The nuts were tightened with a wrench to a torque in the range of 34.0 to 41.0 N.m according to the manufacturer’s specifications in order to limit the shear stress due to the torsion on the anchor.

**Figure 3** – Beam strengthened with bonded CFRP fabrics and using anchor spikes.

**Figure 4** – Beam strengthened with mechanically fastened CFRP pre-cured laminate

### 6. TEST SET-UP & PROCEDURES

All beams were tested for fatigue over a simply supported span of 1829 mm. A sketch of the test set-up is shown in Figure 1-a. All beams were cycled under fatigue loading between a minimum 33% and maximum 63% of the ultimate moment carrying capacity of the section. Subjecting the beams to the same percentage of the ultimate moment capacity seemed an appropriate method to compare fatigue performance of fabrics strengthened and pre-cured laminate strengthened beams with different capacity. The tests were terminated either when the beam failed or reached to 2-million cycles, whichever occurred first. The frequency applied during the fatigue testing was 2 cycles per seconds (2 Hz). Prior to actual fatigue testing, a 10-cycle fatigue test was performed 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 10-cycle fatigue test in order to capture adequate number of data points. The same tests were performed during the fatigue testing after every 500K, 1000K, 1500K and 2000K cycles and the corresponding stiffness was determined.

### 7. EXPERIMENTAL RESULTS

#### 7.1 Fatigue Test Results

All beams survived 2-million cycles except the un-strengthened control sample which failed during cyclic loading at 1.4-million cycles. The initial and 1-million stiffness measurements for the control sample were 7.73 kN/mm and 6.28 kN/mm, respectively (see Figure 5). This corresponds to a decrease of 19% at 1-million cycles as compared to initial cycle. The stiffness mentioned herein is defined as the slope of the load vs. mid-span displacement relation between the maximum and minimum specified loads. Figure 5 shows the measured stiffness versus number of cycles for the strengthened beams. As shown in Figure 5, it was observed that most of the stiffness loss occurred between first and 500K cycles. The highest change in stiffness was observed in CFRP pre-cured laminate strengthening with mechanical fasteners by 22% at 2-million cycles as compared to initial cycle. All others showed a decrease of 15% on average at 2-million cycles.
7.2 Flexural Test Results

All of the strengthened beams were tested under flexural loading after the completion of 2-million fatigue cycles. The flexural tests were performed under four point bending and mid-span displacements were recorded using LVDT. Table 3 compares the expected and the measured failure loads. Figure 6 shows the load versus mid-span displacement curves.

Table 3 – Expected and Measured Failure Loads.

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>Strengthening Description</th>
<th>$\frac{E_s A_s + E_f A_f}{E_s A_s}$</th>
<th>Expected Failure Load [kN]</th>
<th>Measured Failure Load [kN]</th>
<th>Normalized Failure Load* [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-0</td>
<td>Un-strengthened</td>
<td>1.000</td>
<td>28.9</td>
<td></td>
<td>---</td>
</tr>
<tr>
<td>S-1</td>
<td>CFRP fabric (S-1)</td>
<td>1.179</td>
<td>57.5</td>
<td>63.0</td>
<td>53.5</td>
</tr>
<tr>
<td>S-2</td>
<td>CFRP fabric with anchor spikes (S-2)</td>
<td>1.179</td>
<td>57.5</td>
<td>89.5</td>
<td>75.9</td>
</tr>
<tr>
<td>S-3</td>
<td>CFRP pre-cured laminate with epoxy (S-3)</td>
<td>1.449</td>
<td>81.1</td>
<td>80.4</td>
<td>55.5</td>
</tr>
<tr>
<td>S-4</td>
<td>CFRP pre-cured laminate with wedge anchors (S-4)</td>
<td>1.449</td>
<td>82.3</td>
<td>71.1</td>
<td>49.1</td>
</tr>
</tbody>
</table>

* The specimen failed after 1.4-million cycles
** Column 5 divided by column 3

As shown in Table 3, beam S-2 exhibited a 42% higher capacity as compared to beam S-1. The increase in capacity can be attributed to the presence of the anchor spikes, which prevented premature peeling of CFRP fabric. The measured loads were also normalized in order to yield a fair analysis between the different strengthening techniques (see Table 3). The normalization was performed by dividing the measured loads by the axial stiffness ratio of total tension strengthening (CFRP + steel) over steel reinforcement stiffness. As shown in Table 3, beam S-2 and S-3 exhibited failure loads which were 42% and 4% higher than S-1, respectively; however, S-4 showed a failure load which was 8% lower than S-1. The relative slip between concrete and pre-cured laminate that might occur in the case of the beam strengthened using the MF-FRP system explains the lower value of strength as compared with the beams strengthened with the bonded
system. In fact, the engagement between fasteners and the FRP pre-cured laminate was complete after the steel yielded. This phenomenon allowed for a larger magnitude of crack propagation.

The control sample (S-0) failed during fatigue cycling by steel yielding. The crack size increased from 0.55 mm (first cycle) up to as high as 2.50 mm (prior to failure). This caused an increase in reinforcing steel stress until yield of steel attained and caused the failure of beam. The recorded strain level at mid-steel at constant moment zone during highest load level was 0.17% at 1-Million cycles. The reading showed 0.04% strain at initial cycle. After cycling the remaining beams were statically loaded in flexure to failure. The CFRP fabric applied sample (S-1) failed by concrete crushing followed by concrete cover delamination and CFRP rupture. The failure mode of beam S-2 was delamination of CFRP fabric at the mid section between anchor spikes at both ends. Both beams exhibited very similar mid-span displacement readings at failure load and both failures were instant and catastrophic. The beam strengthened with FRP pre-cured laminate bonded with epoxy (S-3) failed at a load of 13% higher than the beam strengthened with MF-FRP system (S-4). While the failure of the beam S-3 was catastrophic, the failure of the beam S-4 was very ductile. As for S-3, after the compression crushing of the concrete the pre-cured laminate peeled off at one side of the beam. On the other hand, for the beam S-4; 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.

![Graph showing Load vs. mid-span displacement curves till test beams failure.](image)

8. CONCLUSIONS & DISCUSSIONS

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 2000K cycles as compared to initial cycle was approximately the same for all the beams (15%) except beam S-4 (22%). This is due to the fasteners which allowed greater crack formation and propagation until the complete engagement of the strengthening;
- Based on the flexural test results, it can be concluded that the analytical design using ACI Committee 440.2R-02 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 pre-cured laminate which showed a load at failure 13.6% lower than the expected value. This can be partially attributed to the higher damage accumulation in the FRP pre-cured 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-4 was 3.5 times of beam S-3;

The use of anchor spikes resulted in a significant increase (about 42%) in the ultimate capacity of the beam as compared to CFRP strengthened beam without anchor spikes. The increase in labor costs using this anchorage technique could be offset by a reduction in the flexural reinforcement used.

9. ACKNOWLEDGEMENTS

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10. REFERENCES