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# Performance of FRCM Strengthened RC Beams Subject to Fatigue

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## ABSTRACT

Fabric reinforced cementitious matrix (FRCM) is a relatively new material system recently developed for the repair, retrofit, and rehabilitation of reinforced concrete (RC) and masonry structures. Concrete structures such as bridges experience high traffic volumes and varying vehicle axle weights causing repeated cyclic loading throughout their lifetime. Cyclic loading may cause damage to the structure, a phenomenon known as fatigue. Due to the novelty of FRCM technology, there is a lack of research regarding the long-term performance of FRCM systems for RC strengthening. This study aims to investigate experimentally the parameters that most influence the flexural fatigue performance of Polyparaphenylene benzobisoxazole (PBO) FRCM strengthened RC beams. For members subject to cyclic loading, a stress ratio vs. the number of cycles (S-N) curve is developed with the objective of defining the endurance limit of the strengthened beams. Failure mode and fatigue life of the beams during cyclic loading are investigated and discussed.

## INTRODUCTION

The repair and rehabilitation of reinforced concrete (RC) structures is motivated by several factors including aging, change in use, increased loads, impact damage, poor construction, code compliance, and environmental damage (e.g. corrosion). In particular, the strengthening of RC structures is a recurring challenge in current transportation infrastructures. Additionally, bridges experience a large number of repeated loading due to vehicular traffic. When subject to cyclic loads, materials experience the phenomenon known as fatigue [Bizindavi 2003]. Many studies have been conducted to evaluate the fatigue performance of conventional RC showing that fatigue failure is predominantly dependent on the steel reinforcement, and rarely controlled by concrete. When the strengthening of fatigue-prone structures is required, the repaired system needs to maintain a favorable long-term fatigue performance.

Existing externally bonded strengthening technologies based on organic matrices referred to as fiber-reinforced polymer (FRP) and more novel solutions based on inorganic matrices known as fabric reinforced cementitious matrix (FRCM) systems have proven to successfully increase and restore strength in RC structures. FRP composites consist of glass, carbon, or aramid fibers embedded in a polymer matrix. The great success of using FRP composites in repair and rehabilitation was driven by their high strength to weight ratio, high tensile strength, and non-corrosive properties. Despite all of these documented advantages, FRP has some limitations: poor behavior at temperatures greater than the glass transition temperature of the resin, inability to bond to a wet surface, lack of vapor permeability, and degradation when subjected to UV light. One possible solution to address these limitations is the replacement of the organic binder with a cementitious binder. Accordingly, FRCM systems consist of one or more carbon, glass, aramid, or Polyparaphenylene benzobisoxazole (PBO) fabrics that are sandwiched between layers of cementitious mortars. FRCM systems possess an inherent resistance to heat and excellent compatibility with the concrete substrate (i.e., can be applied on a wet surface and allow vapor permeability). Unlike FRP composites, dry fabrics imply that the fibers are not impregnated with an organic resin. Much research has been reported on reinforced and prestressed concrete structures strengthened with FRCM subjected to monotonic loading [Babaeidarabad et al., 2014; Pino et. al., 2015], but little to no studies on the fatigue performance of FRCM-strengthened RC have been reported. Accordingly, this paper reports on the evaluation of 11 FRCM-strengthened RC beams subject to monotonic and fatigue loading where fatigue life and failure modes are investigated.

## EXPERIMENTAL INVESTIGATION

**Beam Design.** RC beams were designed per ACI 318-14 to be under-reinforced while exceeding minimum flexural steel requirements and preventing shear failure. Figure 1 shows the beam geometry, reinforcement detailing and the three-point bending configuration used.

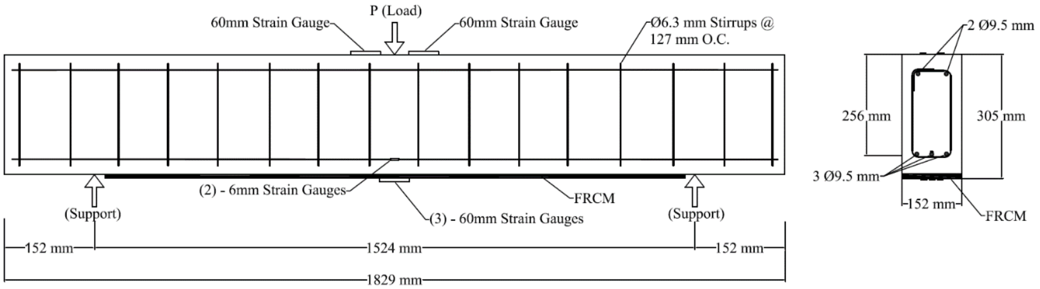

**Figure 1. RC Beam Geometry and Detailing**

RC beams were designed with a concrete strength of 48.3 MPa and steel yield strength of 413.7 MPa and elastic modulus of 199.9 GPa. All constituent materials including concrete and reinforcing steel were characterized to predict the behavior of RC beams. After 28 days, the average strength of five cylinders was 52.5 MPa with a coefficient of variation (COV) of 2.65%. The average yield strength of the steel was 464 MPa with a COV of 1.9%, and the average elastic modulus was 195 GPa with a COV of 2.23%. Beams were strengthened with three externally bonded PBO-FRCM layers applied to the bottom surface.

**FRCM Strengthening.** The FRCM system comprised of a PBO fabric with a stabilized inorganic cementitious matrix. Direct tension tests were performed for one ply continuous, one ply lap, and two-ply specimens. Properties such as modulus of elasticity, ultimate stress, and ultimate strain were determined. The primary mode of failure is due to slippage of the fibers after multiple cracking perpendicular to the direction of the load throughout the length of the specimen. Results from the tensile characterization of a single layer of PBO-FRCM were: 128 GPa cracked elastic modulus ($E_f$), 1,1664 MPa ultimate tensile strength ($f_{fu}$) and 0.0176 mm/mm ultimate tensile strain ($\varepsilon_{fu}$). A detailed description of the specimen preparation, test method, and specimen behavior is given in Pino et al. 2015.

**Test Setup.** A three-point bending test configuration was used for all beams. Beams were instrumented with 6 mm and 60 mm strain gauges as well as three linear variable differential transducers (LVDTs) to measure settlement at the supports and deflections and midspan. Figure 1 shows the test setup as well as the instrumentation layout. Each specimen was tested with a 250 kN hydraulic actuator on a fatigue rated test frame. The applied load was measured using an internal force transducer connected to the actuator.

**Steel and FRCM Reinforcement.** Due to the variety of steel and FRCM reinforcement types as well as differences in material properties, reinforcement ratios ($\rho_s$, $\rho_f$) and experimental elastic moduli ($E_s$, $E_f$) from tension tests for each material were combined ($E_s\rho_s$, $E_f\rho_f$) to accurately compare the reinforcement contribution from each material. For steel, $E_s\rho_s$ was 1063 MPa. PBO-FRCM strengthening configurations were designed using ACI 549.4R-13 without considering reduction factors. A three-ply configuration was chosen to depict the most realistic strengthening scheme resulting in a nominal 9% increase in design strength. This configuration resulted in an $E_f\rho_f$ value of 56 MPa. The design strength is determined using design material properties of 48.3 MPa concrete 413.7 MPa steel yield strength and 1,664 MPa FRCM ultimate strength. Design values are used only to determine the number of layers used for strengthening. Experimental predictions, monotonic load procedures, and cyclic load procedures are based on experimental values from material characterization.

**Experimental Program and Procedure.** This study evaluated 11 RC beams strengthened in flexure with PBO-FRCM. The beams were divided into two groups: Group A subject to monotonic loading, and Group B subject to fatigue loading. Table 1 contains a description of each beam and their respective group and strengthening type.

Group A (Beams 1 through 3) represented the benchmark specimens and consisted of two un-strengthened RC beams and one strengthened beam with three layers of FRCM. Beams in this group were tested at a load rate of 0.22 kN/sec with a total of 4 quasi-static loading and unloading cycles, followed by a displacement-controlled load rate of 0.032 mm/sec up to failure. All loading procedures were determined based on predicted ultimate flexural capacity.

Group B (Beams 4 through 11) consisted of two un-strengthened RC beams and six strengthened RC beams with three layers of PBO-FRCM. Each beam in group B was subjected to cyclic fatigue loading resembling that of a sine wave. All cyclic loads were applied until failure of the specimens or 2M cycles, whichever came first. The reference value used herein is the static load at which yielding of the reinforcing steel occurs in the beam. All cyclic loads are referred to as a percentage of static yield (PSY). Based on the simulation of a typical RC slab bridge designed according to AASHTO LFRD 2010, it was decided to use a minimum value of 20% of static yield for all cyclic tests. The purpose of this research is to exceed the fatigue limit for steel in order to observe the fatigue performance of the strengthened beams. Therefore, all maximum load values were chosen to be larger than the maximum permitted values specified by ACI 215R-92 and AASHTO LRFD 2010 which limit the maximum applied stress range in steel reinforcement as well as the maximum applied stress in the concrete. In this research, the applied concrete stresses were below the threshold of 45% of the concrete compressive strength ($f`_c$). ACI 549.4R limits the tensile stress in the steel reinforcement to be 80 PSY during service load. This number has yet to be experimentally verified, therefore, a loading value between 80% and 100% was chosen. The first maximum load was set at 91% of the yield stress in the steel ($f_{sy}$) corresponding to a maximum concrete compressive stress of 40% of $f`_c$. Based on experimental results from the first test, the following maximum load ranges were selected for Group B beams subject to cyclic loading: 87%, 81%, and 76%, as summarized in Table 1. All analyses and predictions were conducted using the experimental yield strength of 464 MPa.

## RESULTS AND DISCUSSION

**Group A RC Beam Specimens.** A summary of all experimental results is given in Table 1. The un-strengthened control beams under static loading reached an average ultimate load of 97.1 kN. Failure consisted of initial yielding of the steel followed by concrete crushing. Calculations without any reduction factor predicted an ultimate load of 89.7 kN which is 93% of the experimental value. Whereas the strengthened RC beam reached an ultimate load of 125.7 kN, which indicates an increase in flexural capacity of 30%. The failure consisted of initial yielding of the steel followed by delamination of FRCM and finally concrete crushing. The predicted ultimate load was 111.7 kN. The experimental load-deflection curves for both monotonically loaded control Beams A-1 and A-3 and the delamination of Beam A-3 is shown in Figure 2.

**Table 1. Test Matrix of Beams and Summary Results**

| Beam | Load Type | External Reinfor-cement | Min | Max | Failure Type | Number of Cycles at failure ×$10^6$ | Max Load (kN) | Predicted Load (kN) | Design Load (kN) |
|---|---|---|---|---|---|---|---|---|---|
| | | | % static yield (PSY) | | | | | | |
| A-1 | Mono-tonic | None | n/a | n/a | Concrete Crushing after Steel Yielding | n/a | 95.7 | 89.6 | 54.7 |
| A-2 | | | | | | n/a | 98.5 | | |
| A-3 | | PBO | | | FRCM Delam. | n/a | 125.7 | 111.7 | 59.5 |
| B-4 | Cyclic | None | 20 | 76 | Steel Fracture | 0.919 | - | | |
| B-5 | | | | | Steel Fracture | 1.46 | - | | |
| B-6 | | PBO | 20 | 91 | Steel Fracture | 0.492 | - | | |
| B-7 | | | 20 | 87 | Steel Fracture | 0.562 | - | | |
| B-8 | | | 20 | 81 | None* | 2.00 | 131.7* | | |
| B-9 | | | | | Steel Fracture | 1.89 | - | | |
| B-10 | | | 20 | 76 | None* | 2.00 | 124.5* | | |
| B-11 | | | | | None* | 2.00 | 119.8* | | |

**Maximum load from monotonic load test performed after 2M cycles of fatigue loading*

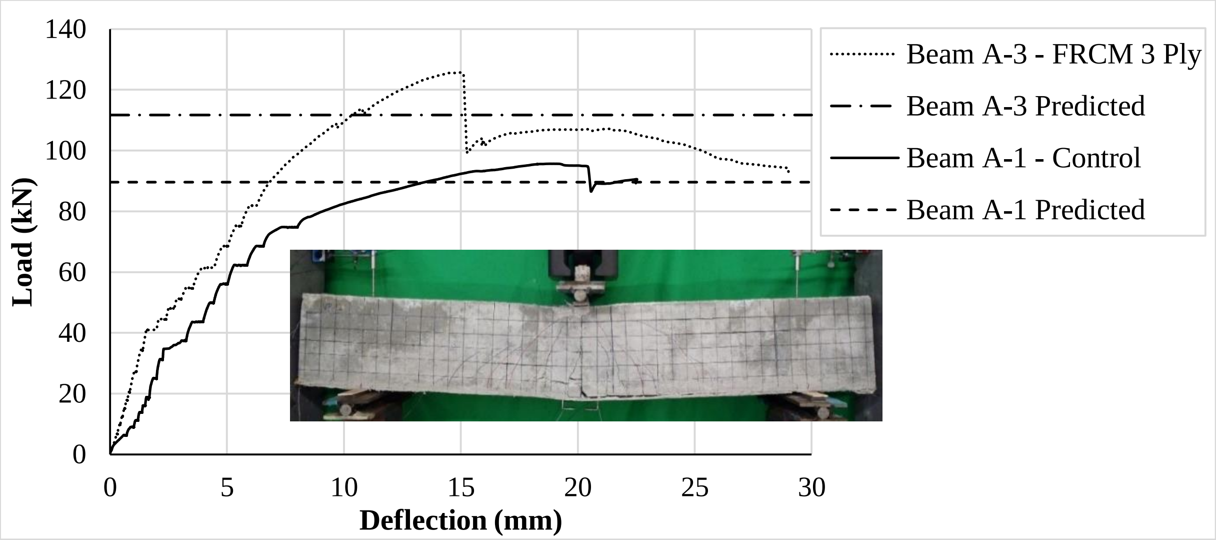

**Figure 2. Load-deflection curves for control and 3-ply FRCM (Delamination Failure)**

**Group B RC Beam Specimens**. Beams subject to 91, 87, and 81% loading of PSY failed due to fatigue rupture of the steel followed by simultaneous delamination of FRCM and concrete crushing. The fatigue life of PBO-FRCM strengthened beams increased with reduced percentage loading of static yield, with the shortest fatigue life of $0.492\times10^6$ cycles for Beam 6 (91 PSY), $0.562\times10^6$ cycles for Beam 7 (87 PSY), and $1.89\times10^6$ cycles for Beam 9 (81 PSY), reaching close to the 2M-cycle threshold. Beam 8 tested at 81 PSY, reached 2M cycles without failure, reflecting the neighborhood of the fatigue endurance. Similarly, Beams 10 and 11 tested at 76 PSY reached 2M cycles without failure. The un-strengthened (virgin) cyclically loaded RC Beams 4 and 5 were tested to 76 PSY, with fatigue lives equivalent to $0.919\times10^6$ and $1.46\times10^6$, respectively; and both failed due to fracture of the steel. Based on the data collected thus far, a stress ratio versus the number of cycles (S-N) curve is shown in Figure 3 for all beams tested under cyclic loading. A solid marker denotes a failure that occurred before 2M cycles while a hollow marker with an arrow depicts a beam that did not experience failure at 2M cycles.

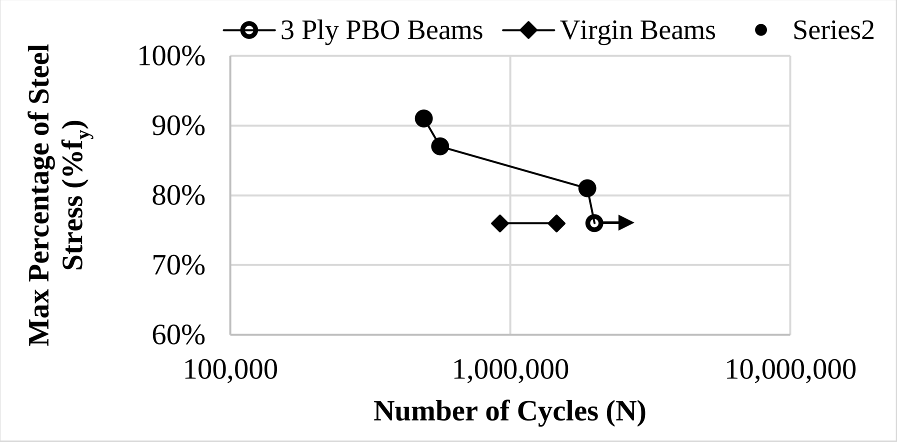

**Figure 3. Load-deflection curves for control and 3-ply PBO-FRCM**

**Flexural Behavior and Failure Mode.** A comparison of the load versus deflection behavior of Group A specimens between an unstrengthened and a PBO-FRCM strengthened RC beam is presented in Figure 2. The benchmark beam exhibited the expected behavior of cracking of concrete when stresses in the tensile zone reached the modulus of rupture followed by yielding of the steel. After significant elongation of the steel rebar and further concrete cracking, the beam failed due to crushing of the concrete. The 3-ply PBO-FRCM strengthened beam exhibited a higher stiffness up to cracking along with a higher yield load. After yielding, the stiffness of the system decreased as the load reached the maximum value (125.7 kN) where the FRCM system delaminated between the first layer of mortar applied to the substrate and the first fabric. Delamination then continued to propagate along the length of the beam from the mid-span to the support. When full delamination occurred, the load-deflection behavior resembled that of the control beam. Based on the experimental results, the PBO-FRCM successfully increased stiffness, yield point, and ultimate load capacity.

For the beams in Group B failing before 2M cycles, distinct failure mechanisms were observed. During the first stage of cycles, numerous cracks formed and propagated along the height of the beam. The FRCM strengthening experienced local debonding from the concrete, where cracks propagated along the concrete-FRCM interface. In the second stage, the concrete cracks continued to grow at a lesser rate except one primary flexural crack that steadily propagated towards the compressive zone. During this stage, minimal local FRCM debonding occurred. Cracks then initiated at the rebars height, areas of high-stress concentration (rib root), and propagate along the cross section. During the final stage, brittle fracture occurred in the steel followed by complete delamination of the FRCM as the ram (in load control) attempted to reach the preset maximum load.

**Fatigue Life.** The experimental results show that beams in Group B subjected to a higher load range experienced shorter fatigue lives. The shortest fatigue life occurred in Beam 6 with a maximum loading of 91 PSY followed by Beam 7 at 87 PSY. Beams 8 and 9 were tested at 81 PSY while only Beam 9 failed slightly below 2M cycles and Beam 8 reached the 2M-cycle limit. Beams 10 and 11 were then tested to 76 PSY and both successfully reached 2M cycles without fatigue failure. It was observed that the rate of crack propagation decreased with a decreasing maximum load, specifically in the early cycles of loading. Results suggest that if stress in the steel reinforcement is below 76 PSY and with an $E_s\rho_s$ value of 1063 MPa and $E_f\rho_f$ value of 56 MPa, there will be no failure due to fatigue in the reinforcement up to 2M cycles and most likely the entire life of the structure. Control Beams 4 and 5 were tested up to 76 PSY for comparison purposes; both beams experienced failure due to steel fracture before reaching 2M cycles. This result suggests that FRCM as a strengthening technology may improve the fatigue life of RC beams. In addition, it was also observed that the FRCM mitigated crack opening in the flexural surface (bottom of the beam), which potentially slowed the crack propagation compared to an un-strengthened RC beam.

## CONCLUSION

The work presented herein is a preliminary evaluation of the fatigue performance of PBO-FRCM strengthening technology. To account for differences in reinforcing material properties, the axial stiffness ($E_s\rho_s$, $E_f\rho_f$) was used to compare the contribution of each material. Based on the experimental results, the following conclusions can be inferred:

- The application of PBO-FRCM to RC beams provides an increase in strength, yield point, and stiffness, with delamination from the concrete substrate, was the main failure mode.
- All observed fatigue failure mechanisms were due to steel fracture.
- The level of minimum and maximum stresses in the reinforcing steel are critical parameters in the fatigue life of RC beams strengthened with an $E_f\rho_f/E_s\rho_s$ of about 5%.
- Fatigue life decreases with increase in maximum applied load up to an endurance limit of 76 PSY.
- If the stress in steel is below 76 PSY for an RC beam strengthened with FRCM, no failure due to fatigue in the reinforcement was experienced up to 2M cycles.

Further research evaluating the fatigue performance of RC beams strengthened with various modified FRCM-steel reinforcement ratios needs to be conducted.

## ACKNOWLEDGEMENT

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