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Fatigue Performance of FRCM Strengthened RC Beams Subjected to Environmental Exposure and Varied Frequencies

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Abstract
Progressive and localized structural damage occurs when materials are exposed to oscillated loads at a certain stress limit. This is the case for reinforced concrete beams in bridge applications. This study focused on the fatigue performance of a fiber reinforced cementitious matrix (FRCM) composite used to repair reinforced concrete beams to determine its capability in relative to fatigue and environmental exposure in bridge rehabilitations. Specifically, this paper examined the effect of different environmental exposure and fatigue frequency on the strengthened beams' stiffness performance. A monotonic flexural test followed two million successful cycles of fatigue loading. The capability of a FRCM composite in resisting fatigue loadings under severe environmental conditioning were also determined. Beam stiffness degradation ranged between 12% and 23% based on the exposure conditions, the FRCM reinforcement ratio, the fatigue frequency, and the concrete strength. The FRCM system yielded positive overall fatigue resilience even when exposed to severe conditioning.

Keywords: FRCM; beams; frequency; environment; fatigue; flexure.

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Introduction

Most infrastructure systems are externally vulnerable over time to various environmental deteriorations such as freeze-thaw cycles, wet-dry cycles, high temperature exposure, and high relative humidity. In such cases, potential problems with concrete including micro and macro cracking, scaling, and spalling might influence the life span of structural members. As a result, many older infrastructure elements or structures have been characterized as structural deficient and in need of serious repair [1]. During the last two decades, fiber reinforced polymer (FRP) systems have been developed and deployed for retrofitting and strengthening applications [2]. However, a new generation of composite material called fiber reinforced cementitious matrix (FRCM) have overcome certain FRP system limitations. The FRCM composite has the capability to be exposed to fire without producing toxic fumes as materializes from an epoxy binder [3]. The FRCM composite has the same chemical, physical, and mechanical features of the concrete substrate to which it is applied so the installation process is often easier and faster [3]. Aljazaeri and Myers [4] conducted the first major study on full-scale RC beams strengthened with FRCM composite and subjected to service bridge loadings. The results of eight beams observed that the FRCM composite was able to resist fatigue loadings up to two million cycles without significant degradation in the beam stiffness. The other reported study by Pino et al. [5] examined the influence of the internal steel reinforcement ratio on the fatigue performance of the strengthened RC beams with FRCM composite. The experimental results limited the level of fatigue stresses to be below 76% from the static yielding of the internal steel reinforcement and also limited to the FRCM composite' reinforcement ratio in order to prevent a fatigue failure in the steel reinforcement [5]. On the other hand, Akbari Hadad et al. [6] reported that the fatigue endurance limit of carbon FRCM-strengthened beams was only 65% of the static yielding load capacity and the FRCM composite increased the fatigue life of strengthened beams with respect to unstrengthen one. Elghazy et al. [7] experimentally determined that fatigue life of the corrosion-damaged beams restored by 38% – 377% of that of unstrengthened beam depending on the type and configuration of the FRCM used. Though, the effect of severe environmental exposure and fatigue, which can negatively interfere with the bond performance of the structural elements and composite material, is necessary to be investigated. In view of this, this investigation highlighted some essential fatigue and flexure features of the FRCM strengthened beams under natural exposure. As well, the other RC FRCM strengthened beams were tested for different fatigue frequency to determine its effect on beam stiffness degradation. In addition, test results of the strengthened beams were compared with the previous findings by Aljazaeri and Myers [4]. The experimental marks are evaluated in terms of beam stiffness degradation, load-carrying capacity, and failure mode.

Description of Test Specimen, Test Matrix, FRCM Strengthening and Testing

Typical beam dimensions and reinforcement details are shown in Fig. 1. Ready-mix concrete was used to cast the beams. The average compressive strength of the concrete was 38.4 MPa (5,570 psi) using ASTM C39 [8]. The concrete's modulus of elasticity was approximately 30 GPa (4,400 ksi) using ASTM C469 [9]. The coupons' average tensile strength was about 482 MPa (70 ksi) and the average ultimate strength was 538 MPa (78 ksi) in accordance to ASTM A370 [10]. The average tensile strength of FRCM coupons was

1240 MPa (180 ksi) with an ultimate strain of 0.007 mm/mm (in./in.) based on standard test method AC 434 [11]. The modulus of elasticity of FRCM coupons before and after cracking were about 2,600 MPa (377,000 ksi) and 131 MPa (19,000 ksi), respectively. The average compressive strength of five cubes of the cement-based binding agent was 32 MPa (4,700 psi) at 28 days following ASTM C109 [12]. The test matrix is presented in Table 1. All the RC beams were first pre-cracked by 65% of their design ultimate strength after 28 days of curing of their ultimate design capacities based on ACI 440 (2008) and ACI 549 (2013). After pre-cracking the specimens, the application of the FRCM composite followed using the recommendations of AC 434 [11].

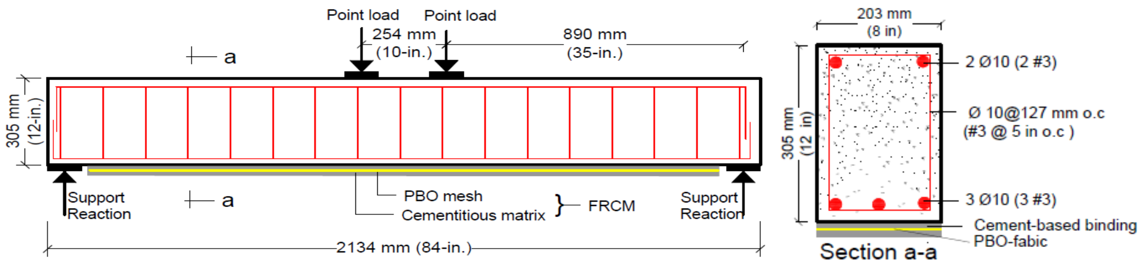


Fig. 1. RC Beam geometry and reinforcement details

Two of the beams (Beams B7-1 and B8-4) were placed inside the environmental chamber for 72 exposure days after curing period. The exposure cycles included 50 cycles of freezing and thawing, 150 cycles of high temperature, and 150 cycles of high relative humidity. It was based on collected data from the National Weather Service and Worldwide Weather Station for Missouri weather in the United States from 1980 to 2013 [13,14]. Aljazaeri and Myers [15] may be referenced for more details regarding the exposure details. Then, all the beams were subjected to fatigue loading amplitudes that ranged between 35% and 65% of the beams' ultimate design strength for two million cycles. Sixty-five percent was selected as the maximum fatigue loading to be similar to the service level loading that elements would normally be expected to see under field loading conditions. After fatigue cycling was done, all the beams were tested under a four-point flexural loading at a rate of 1.3 mm/minute (0.05 in./min) up to failure.

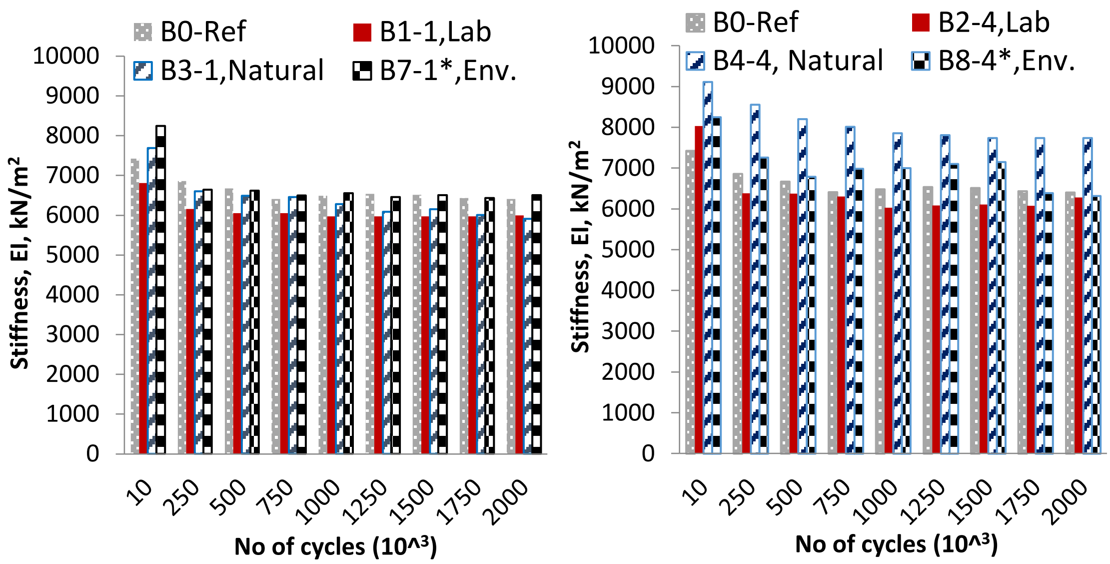
Table 1: Test Matrix

Specimen ID	Conditions	FRCM	# Plies	Freq., HZ
B0-Ref*	Laboratory conditions	N/A	N/A	5
B1-1*	Laboratory conditions	FRCM	1	5
B2-4*	Laboratory conditions	FRCM	4	5
B3-1	Natural exterior weathering environment (18 months)	FRCM	1	5
B4-4	Natural exterior weathering environment (18 months)	FRCM	4	5
B5-1	Laboratory conditions	FRCM	1	2
B6-1	Laboratory conditions	FRCM	1	3.5
B7-1*	Environmental chamber cycles	FRCM	1	5
B8-4*	Environmental chamber cycles	FRCM	4	5

*These beams were used for comparison study [4].

Fatigue and Flexural Test Results

All beams mentioned the same fatigue load-displacement behaviour with varies stiffness degradation at the end of 2 million cycles. Fig. 2 illustrates the measured beam stiffness at each 250,000 fatigue cycle. Beam stiffness measurements (EI) were specified at the mid-span displacement point and at the maximum fatigue loading. Beam stiffness was obtained from the load-deflection data collected based on the linear behaviour between the minimum and peak fatigue cycles at the key cycles as shown in Fig. 2. The test results revealed that a higher degradation in beam stiffness occurred during the first 250,000 cycles for all strengthened beams. Then, beam stiffness measurements slightly varied as the fatigue cycles continued to approach 2 million cycles. The fatigue test was terminated at the point of 2 million cycles. In all test cases, the visual expectation to the strengthened beams revealed that no debonding was detected between the FRCM composite and the concrete substrate or between the FRCM layers after 2 million fatigue cycles. The test results for beams exposed to natural weathering conditions were compared to those of the exposed beams to a laboratory and an environmental chamber conditions. The test results of stiffness degradation under different exposure conditions were ranged between 12% up to 23%. However, the stiffness degradation of strengthened beams was not proportionally related to the exposure conditions. The strengthened beams with one FRCM ply under 2, 3.5, and 5 Hz frequencies were also evaluated. A frequency of 2 Hz did not cause any observed stiffness degradation in the beam. However, Beam (B6-1), which was loaded at 3.5 Hz fatigue frequency, exhibited an 18% degradation in its stiffness. While beam (B1-1), which was loaded at 5 Hz fatigue frequency, exhibited a 12% degradation in stiffness. One observation during testing that the crack configurations (numbers, lengths, and widths) were varied from one beam to another. As a result, pre-cracked beams exhibited different initial stiffness, as shown in Fig. 2. Thus, when the beams were subjected to repetitive loading, arbitrary internal fatigue concrete cracks propagate and intersect with each other resulting in stiffness variability. The flexural testing determined that all strengthened beams provided flexural enhancement with respect to the reference beam. Table 2 presented the ultimate load capacity of each tested beams, the percentage enhancement in the flexural capacity with respect to the reference beam, the design ultimate load determined per ACI 549 [1], and the ratio of experimental ultimate load over the design ultimate load. For many of the specimens, the experimental load to design load ratio was nearly 2 which highlights the current conservative nature of ACI 549 standard. The observed failure mode was a slippage of FRCM in case of strengthened beams with one ply and a debonding failure mode in case of strengthened beams with four plies.



(a) 1 FRCM ply (b) 4 FRCM plies

Fig. 2. Beams' stiffness measurements

Table 2. Load carrying capacity

Specimen ID	Experimental ultimate load, kN	% Increase in loads	Design ultimate load, kN	Exp. load/ design load
B0-Ref	97		45	
B1-1	110	13%	53	2.08
B2-4	119	23%	93	1.28
B3-1	120	24%	53	2.26
B4-4	160	65%	93	1.72
B5-1	112	15%	53	2.11
B6-1	117	21%	53	2.21
B7-1*	130	34%	53	2.45
B8-4*	155	60%	93	1.67

Conclusions

The following observations and conclusions determined that the FRCM composite can resist different weather conditions, fatigue loading, and provided flexural enhancement. So the FRCM composite can be used for repairing and strengthening in bridge applications:

1- All of the strengthened beams did not experience any premature failure due to composite system in resisting fatigue loadings.
2- The applied fatigue loading produced varying distributions of network cracks that affected both the initial and final beams' stiffness values. The variation in the beams' stiffness degradation ranged between 12% and 23% which were highly influenced by concrete performance.

3- Within the scope of the work conducted herein, the durability of the FRCM composite was evident for the beams exposed to outdoor and environmental conditions.
4- The flexural loading tests demonstrated that the FRCM composite is an efficient structural material for enhancing the flexural capacity of exposed or unexposed RC beams.
5- The level of fatigue frequency was not proportionally influenced the beams' stiffness degradation.

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