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

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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.

1 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 [ACI, 2013]. During the last two decades, fiber reinforced polymer (FRP) systems have been developed and deployed for retrofitting and strengthening applications [ACI, 2013]. However, a new generation of composite material called fiber reinforced cementitious matrix (FRCM) have overcome certain FRP system limitations. This includes that the FRCM system is less sensitive to higher service temperatures as reported by Al-Jaberi et al. [2019]. Major studies related to topic were undertaken by Aljazaeri and Myers [2016] and Pino et al. [2017]. The first study conducted on full-scale RC beams strengthened with FRCM composite and subjected to service bridge loadings. The test results that strengthened beams were able to resist fatigue loadings up to two million cycles without significant degradation in the beam stiffness, (Aljazaeri and Myers, 2016). The second study 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, (Pino et al., 2017). In view of this, this investigation highlighted some essential fatigue and flexure features of the FRCM strengthened beams under natural exposure.

2 DESCRIPTION OF TEST SPECIMEN AND EXPERIMENTAL WORK

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 [2014]. The coupons' average tensile strength was about 482 MPa (69.9 ksi) and the average ultimate strength was 538 MPa (78.0 ksi) in accordance to ASTM A370 [2012]. The average tensile strength of FRCM coupons was 1240 MPa (179.8 ksi) with an ultimate strain of 0.007 mm/mm based on standard test method AC 434 [2013]. The PBO mesh tensile properties are presented in Table 1 as measured by the manufacturing company. The tensile strength of the PBO mesh in the main direction was about four times that in the secondary direction. The mechanical properties of the FRCM strengthening system were developed in this study based on the recommendations of the AC 434 (2013). Five 50 mm cubes were tested to determine cementitious mortar's compressive strength. The average compressive strength of the cubes was 31 MPa (4,500 psi) at 28 days in accordance with ASTM C109 (2013). Five FRCM coupons were prepared from the same batch that was used to strengthen the RC beam specimens in order to characterize the FRCM's mechanical properties. Laboratory preparation and testing of the FRCM coupons were conducted following the AC 434 protocol (2013). The test matrix is presented in Table 2.

Table 1. Mechanical properties of FRCM coupon specimens

PBO Property (Ruredil Company)	**Symbol**	**Mean results**
Ultimate tensile stress in main direction, kN/m	F_{fu}	2640
Ultimate tensile stress in the secondary direction, kN/m	F_{fu}	665
FRCM Laboratory Tested Property	**Symbol**	**Mean results**
The uncracked specimen's modulus of elasticity, MPa	E^*_f	1360
The cracked specimen's modulus of elasticity, MPa	E_f	127
Ultimate tensile strength, MPa	F_{fu}	1200
Ultimate tensile strain, mm/mm	ε_{fu}	0.007
Fiber area by unit width, mm^2/mm	A_f	0.006

All the RC beams were first pre-cracked by 65% of their design ultimate strength after 28 days of curing. The application of the FRCM composite followed the recommendation of AC 434 [2013]. Two beams were conditioned in a natural environment in Rolla, Missouri, USA for 18 months, while two other beams were conditioned in an environmental camber subjected to various sustained stress, temperature and humidity cycles. Aljazaeri and Myers [2018] may be referenced for more details regarding the environmental chamber exposure details. The remainder were only subjected to labratory conditions. Then, all the beams were subjected to fatigue loading amplitudes that ranged between a minimum 35% and maximum 65% of the beams' ultimate design strength for two million cycles, using ACI [2013] to estimate the members design strength. After fatigue testing, all the beams were tested under a four-point flexural loading at a rate of 1.3 mm/minute up to failure.

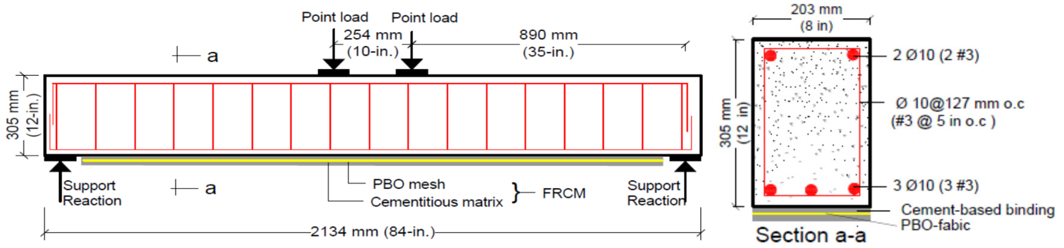


Fig. 1: RC beam geometry and reinforcing details

3 DISCUSSION

All beams with the same fatigue load-displacement behavior with varies stiffness degradation at the end of 2 million cycles. 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 then test was terminated. 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. The test results of stiffness degradation under different exposure conditions 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 Table 1. 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, as shown in Table 2. The percentage enhancement in the flexural capacity were ranged between 13% to 65% based on the provided FRCM reinforcement ratio. 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.

Table 2: Summary of test results and flexural results

Specimen ID	Conditions	FRCM	# Plies	Freq., Hz	Stiffness degradation, %	Ultimate Load, kN
B0-Ref	Laboratory conditions	N/A	N/A	5	14%	97
B1-1	Laboratory conditions	FRCM	1	5	12%	110
B2-4	Laboratory conditions	FRCM	4	5	22%	119
B3-1	Natural exterior weathering environment (18 months)	FRCM	1	5	23%	120
B4-4	Natural exterior weathering environment (18 months)	FRCM	4	5	15%	160
B5-1	Laboratory conditions	FRCM	1	2	0%	112
B6-1	Laboratory conditions	FRCM	1	3.5	18%	117
B7-1	Environmental chamber cycles	FRCM	1	5	21%	130
B8-4	Environmental chamber cycles	FRCM	4	5	23%	155

This portion of the study examined the sensitivity of the fatigue loading frequency relative to the FRCM strengthening system. Three beams were selected and strengthened with one FRCM ply. One strengthened beam was subjected to a 2 Hz frequency, the most common real-world cycling frequency in bridge applications. Two other higher fatigue frequencies of 3.5 Hz and 5 Hz, were selected respectively. Fig. 2 presents the beam stiffness measurements comparison between these cyclic ratios. A frequency of 2 Hz did not cause any observed stiffness degradation in the beam. This means that the 2 Hz frequency is not high enough to cause stiffness degradation with respect to the FRCM strengthening and applied fatigue loading. However, increases in the fatigue frequency resulted in a readily observed reduction in the beam stiffness under the same level of fatigue loadings. 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. Both higher frequency rates displayed much of their stiffness reductions during the initial 250,000 cycles then stabilized. The stiffness degradation was scattered with respect to various fatigue frequency. The authors recommended to test three beams for each value of fatigue frequency to estimate the effect of fatigue frequency on the beams stiffness degradation properly.

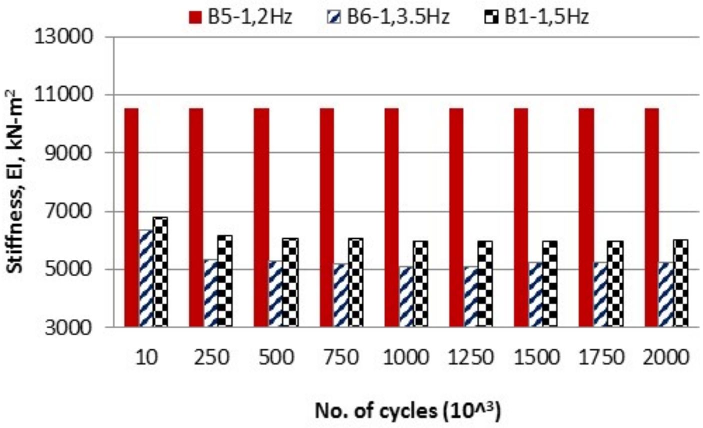
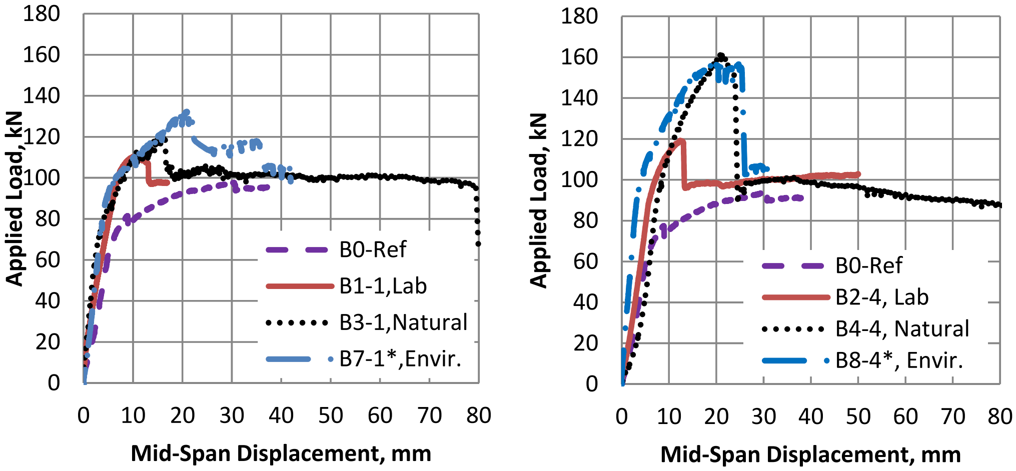


Fig. 2. Beams' stiffness measurements under different fatigue frequency

The results of the flexural loading test that followed the 2 million cyclic loading are presented here. A comparison of the load versus mid-span displacement is presented in Fig. 3. All strengthened beams provided flexural enhancement with respect to the reference beam. However, the beams exposed to natural weather conditions reached an ultimate load of 120 kN (27 kips) for one ply and 160 kN (36 kips) for four plies. As well, the exposed beams to environmental chamber conditions revealed an ultimate load of 130 kN (29 kips) for one ply and 155 kN (36 kips) for four plies. Thus, the exposed beams to the natural or environmental chamber conditions indicates an increase in the flexural capacity higher than the flexural capacity of the unexposed beams. This flexural enhancement occurred due to additional curing time inside the environmental chamber or exterior exposure. A higher presence of moisture and higher temperature cycles compared to laboratory conditions improved the properties of matrix and thereby the bond performance of the FRCM composite and its load carrying ability.



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

Fig. 3. Load-displacement curves for flexure test preceding fatigue test

Fig. 4 presented the load versus mid-span displacement for the strengthened beams that were subjected to different fatigue frequency. The strengthened beams had a similar flexural behavior under different fatigue frequency. The beam that was cycled at a 3.5 Hz frequency resulted in the highest ultimate load compared to beams that were cycled at 2 Hz and 5 Hz frequency, respectively. It can be determined that the fatigue frequency level between 2 Hz and 5 Hz mentioned the beams in an elastic fatigue platform. Therefore, the fatigue frequency level was not impact the beams' ultimate load capacity.

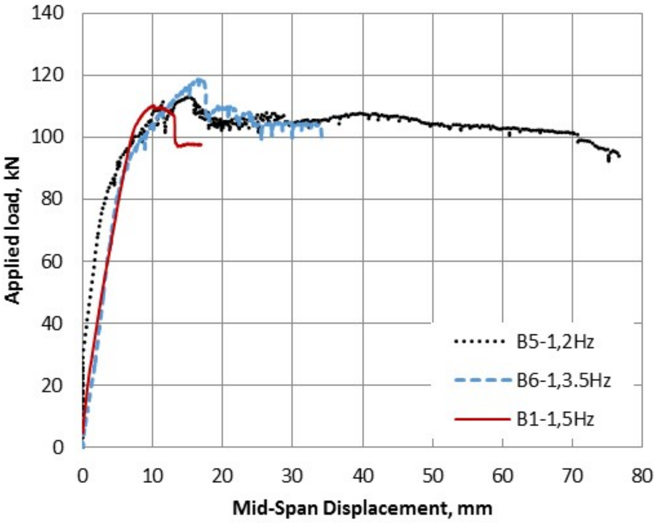


Fig. 4: Load-displacement curves for flexure test preceding different fatigue frequencies

4 CONCLUSIONS

The fatigue and flexural performance of the FRCM strengthened beams was experimentally studied in this work. The unstrengthened and strengthened beams were tested under cyclic fatigue loading. Some of the beams were exposed to outdoor weather conditions and environmental conditioning to evaluate the long-term durability of the new-innovative FRCM composite technology. The other beams were subjected to different fatigue frequencies. 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 loading in bridge applications.
2- The applied fatigue loading produced varying distributions of network cracks that affected both the initial and final beams' stiffness values.
3- The variation in the beams' stiffness degradation ranged between 12% and 23% which were highly influenced by concrete performance.
4- The strengthening system exhibited lower degradation levels in beam stiffness (less than 23% of the initial beams' stiffness after 2 million fatigue cycles) and demonstrated the suitability of the FRCM composite.
5- 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.
6- 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. In the case of beams subjected to environmental or outdoor exposure, higher ultimate loads resulted due to additional curing time which enhanced the cement-based binding properties in turn the FRCM composite performance.
7- The FRCM composite proved its effectiveness under 2 Hz frequency (the practical fatigue frequency in bridge application) with zero stiffness degradation. As well, the FRCM composite retain more than 80% of the beams' stiffness under higher frequency of 3.5 Hz and 5 Hz. The level of fatigue frequency was not proportionally influenced the beams' stiffness degradation.
8- Varying fatigue frequency or exposure condition did not affect the failure mode of the strengthened beams under flexural loading. It was only influence by the FRCM reinforcement ratio.

5 REFERENCES

ACI (American Concrete Institute). (2013). "Guide to design and construction of externally bonded fabric-reinforced cementitious matrix (FRCM) systems for repair and strengthening concrete and masonry structures." ACI 549, Farmington Hills, MI.

AC 434. (2013). "Acceptance criteria for masonry and concrete strengthening using fabric-reinforced cementitious matrix (FRCM) composite systems." ICC-Evaluation Service, Whittier, CA.

Al-Jaberi, Z.K., Myers, J.J., Chandrashekhara, K. (2019) "Effect of direct service temperature exposure on the bond behavior between advanced composites and CMU using NSM and EB techniques," Elsevier's Composite Structures Journal, https://doi.org/10.1016/j.compstruct.2018.11.085, Vol. 211, pp 63-75.

Aljazaeri, Z., and Myers, J.J. (2016). "Fatigue and flexural behavior of reinforced concrete beams strengthened with a fiber reinforced cementitious matrix," ASCE Journal of Composites for Construction, 10.1061/(ASCE)CC.1943-5614.0000696.

Aljazaeri, Z.R. and Myers, J.J. (2018) "Flexural performance of reinforced concrete one-way slabs strengthened with composite materials," ASCE – Journal of Materials in Civil Engineering, 30(7).

ASTM C39. (2014). "Standard test method for compressive strength of cylindrical concrete specimens." ASTM International, West Conshohocken, PA.

ASTM A370. (2012). "Standard test methods and definitions for mechanical testing of steel products." ASTM International, West Conshohocken, PA.

Pino, V., Akbari Hadad, H., De Caso y Basalo, F., Nanni, A., Ali Ebead, U., and El Refai, A. (2017). "Performance of FRCM-strengthened RC beams subject to fatigue." ASCE Journal of Bridge Engineering, 22(10), 04017079.