- Technical Paper -

A STUDY ON PERFORMANCE IN FLEXURE OF RC BEAMS STRENGTHENED WITH PRECAST CARBON-FRCM PLATE COMPOSITES

Liangliang WEI*1, Meini SU*2, Tamon UEDA*3 and Ji-Hua ZHU*4

ABSTRACT

Fabric reinforced cementitious matrix (FRCM) represents an innovative composite for structural strengthening. This paper presents the flexural performance of Carbon-FRCM strengthened RC beams under static and fatigue loading. The precast Carbon-FRCM plate was adopted instead of cast-in-situ FRCM. Results show that it is effective in strengthening and prolonging fatigue life of RC beams. The layers of carbon fabric mesh in precast Carbon-FRCM plate controlled the failure mode of beams in static loading and fatigue properties of steel bars was the governing factor for fatigue life of beams.

Keywords: precast Carbon-FRCM, structural strengthening, flexural performance, static, fatigue

1. INTRODUCTION

Structural strengthening has been proven to be one of the most effective methods in rehabilitation of deteriorated reinforced concrete (RC) structures [1]. Compared to strengthening with FRP composites, an alternative fabric reinforced cementitious matrix (FRCM) composite has recently emerged in structural strengthening [2, 3]. The characteristic of FRCM compared to FRP strengthening system is to use the cement-based material replacing the epoxy resin to bond the fabric reinforcement onto RC structures. In accordance with fabric properties, FRCM composites have a general classification as Carbon-FRCM with carbon fabric, PBO-FRCM with polyparaphenylene benzobisoxazole (PBO) fabric, Glass-FRCM with alkali resistance (AR) glass fabric. As a promising composite, the performance of structures strengthened with FRCM has been investigated in recent years.

Significant research contributions have been made on FRCM composites for flexural strengthening on RC beams. Wiberg [4] reported the static performance of RC beams using cementitious carbon fiber composites, in which a slightly increase of the failure load ranging from 10% to 20% was obtained. This was probably due to the use of carbon fiber sheet with poor penetration between cementitious matrix and carbon fiber sheet. Therefore, the fiber sheets typically used in FRP are replaced by the structural reinforcing mesh or fabric in FRCM. D'Ambrisi and Focacci [5] discussed the results of RC beams strengthened in flexure with Carbon and PBO meshes, in which PBO-FRCM performed better than Carbon-FRCM due to the higher effective usage of fabric at failure. The observed failure was almost fabric debonding from the matrix instead of the concrete substrate. The effect of layers of mesh and fabric type in FRCM composites, and axial stiffness of FRCM on the flexural strengthening of RC beams under static loading can be found in [6, 7]. However, limited literatures have reported the flexural performance of FRCM-strengthened beams in fatigue loading. Pino et al. [8] experimentally investigated the flexural fatigue performance of PBO-FRCM-strengthened RC beams. Results showed that the fatigue resistance level of improvement was largely dependent on the layers of mesh in FRCM. All observed fatigue failure was the steel fracture followed by FRCM failure. Although, some preliminary studies provide the confidence that FRCM strengthening system has comparable fatigue enhancement [9, 10]. Further research evaluating the fatigue performance of RC beams strengthened with FRCM composites needs to be conducted.

Installation of FRCM adopted, at present, is almost a cast-in-situ construction procedure [6, 11]. The fiber bundle of fabric is unconsolidated that make obvious variation happen from the intended direction easily in the process of assembling FRCM composite in the field. It is possible to cause a substantial reduction in strengthening performance. Therefore, the fiber alignment in primary direction should be taken into consideration in the installation of FRCM for strengthening. One of contributions in this paper is to provide a method for maintaining the fiber bundle straightness and orientation in Carbon-FRCM composite. The precast Carbon-FRCM plate composite for strengthening is proposed. The other contribution is to use this kind of precast Carbon-FRCM plate strengthening RC beams to investigate the flexural performance under static and fatigue loading.

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*1 Laboratory of Engineering for Maintenance System, Hokkaido University, JCI Student Member
*2 Associate Prof., School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Dr. E.
*3 Professor, Faculty of Engineering, Hokkaido University, Dr. E., JCI Member
*4 Professor, School of Civil Engineering, Shenzhen University, Dr. E. Corresponding author

2. TEST PROGRAMS

2.1 Materials

(1) Concrete

The mixture proportions of concrete, for each cubic meter volume, were 977 kg of coarse aggregate, 652 kg of sand, and 390 kg of ordinary Portland cement. The water-to-cement (w/c) ratio was kept at 0.48. Three standard concrete cubes with dimensions of 150 mm were used to evaluate the compressive strength of concrete. The average cubic compressive strength (f_{cu}) was 42.16 MPa with a standard deviation (SD) of 1.76 MPa.

(2) Steel reinforcing bars

Two deformed steel bars with diameter of 12 mm were placed at the tension zone of beam, while two round steel bars with diameter of 8 mm were placed at the compression zone. The same 8 mm diameter bars were used as stirrups as well. The measured mechanical properties of steel reinforcing bars are constructed in Table 1.

Table 1 Properties of steel bars

Nominal Diameter (mm)	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Modulus of elasticity (kN/mm^2)	Yield strain	Tensile strain
12	496.7	601.3	199.5	0.0025	0.093
8	340	544	200	0.0017	0.130

(3) Carbon fabric mesh and modified paste matrix

The precast Carbon-FRCM plate composites comprise carbon fabric (CF) mesh and modified paste matrix. The unbalanced carbon fabric mesh, as shown in Fig. 1, was made of 5 mm in primary direction and 2 mm in secondary direction. The free space between bundles was around 5 mm. The measured thickness of bundle in both directions, and the tensile properties are constructed in Table 2. The cement-based matrix was prepared that not only considered as the base of precast Carbon-FRCM plate composites but an inorganic glue for bonding. The average 28-day compressive strength of the modified paste matrix was 37.94 MPa with SD of 1.24 MPa.

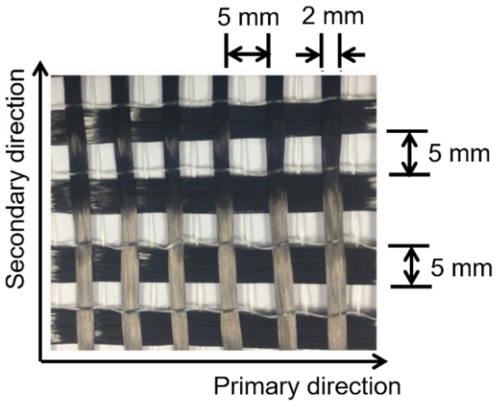


Fig. 1 Geometry of carbon fabric (CF) mesh used in precast Carbon-FRCM plate composite

Table 2 Properties of carbon fabric mesh

Fabric direction	Thickness (mm)	Tensile strength (N/mm^2)	Modulus of elasticity (kN/mm^2)	Tensile strain
Primary	0.155	4061	258	0.0157
Secondary	0.207	3519	223	0.0158

2.2 Precast Carbon-FRCM Plate Composites Preparation

The precast Carbon-FRCM plate composites for strengthening were prepared as illustrated in Fig. 2. The well-fitted wood moulds and CF meshes were prepared before mixing paste matrix. The procedure for preparation of precast Carbon-FRCM plate composites can be described as following: (1) put the ready-mixed paste matrix into the bottom of mould with the thickness of about 5 mm; (2) align the ready-cut CF mesh onto the matrix and straighten the mesh at the both end using proper weight objects simultaneously; (3) cast the matrix with the thickness of 5 mm again covering the mesh. This procedure would be repeated if more than one layer of mesh were embedded into FRCM. In this paper, one and two layers of CF mesh would be embedded where the thickness of precast Carbon-FRCM plate were approximate 10 mm and 15 mm, respectively. The length and width were 1100 mm and 170 mm, respectively. The precast Carbon-FRCM plate composites were cured for 28 days before bonding onto the beams.

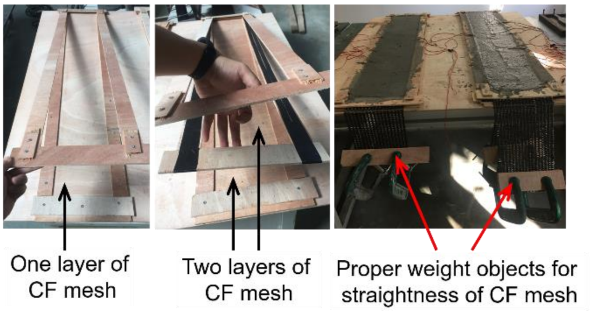


Fig. 2 Preparation of precast Carbon-FRCM plate composites for strengthening RC beams

2.3 Tested RC Beams Preparation

Six reinforced concrete (RC) beams were prepared with dimensions of 1500 mm in length, 170 mm in width, and 300 mm in height, as shown in Fig. 3. Stirrups were placed at interval of 80 mm in the both sides of the beam except the intermediate zone of 400 mm. After 28 days, the precast Carbon-FRCM plates were bonded to the soffit of the beams using the same paste matrix.

Three beams were prepared in static and fatigue tests, respectively, in which one was benchmark beam and two were strengthened with precast Carbon-FRCM plate in one and two layers of CF mesh. The tested RC beams preparation is shown in Table 3. The specimens' ID are denoted by X-Y form where X represents the beam type with Control for benchmark beam, CF1 for strengthened beam with one layer of CF mesh, and CF2 for counterpart with two layers of CF mesh, Y represents loading type with S for static loading and F for fatigue loading.

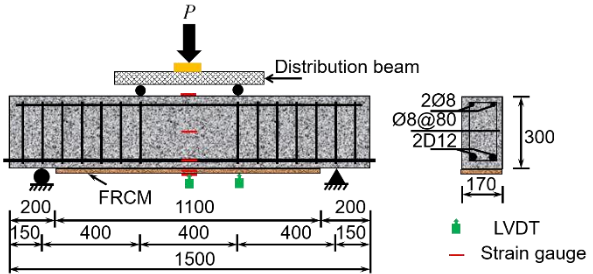


Fig. 3 Geometry of strengthened RC beams and set-up of four-point bending test

Table 3. Tested RC beams preparation

Loading type	ID	Layers of CF mesh in precast Carbon-FRCM plate	Load range, %	
			Max	Min
Static	Control-S	0	N/A	
	CF1-S	1		
	CF2-S	2		
Fatigue	Control-F	0	73	14
	CF1-F	1	73	14
	CF2-F	2	83	14

2.4 Test Set-Up and Procedure

The loading system used a hydraulic servo system, and data were automatically recorded. Fig. 3 shows the set-up of four-point bending test. The applied load was recorded by a load cell placed between the hydraulic head and distribution beam. Deflection at midspan was measured using an LVDT. One strain gauge with a gauge length of 50 mm was attached to the top of the concrete beam at midspan, two strain gauges with a gauge length of 5 mm were attached on the steel reinforcing bars at midspan, and one strain gauge with a gauge length of 2 mm was attached on the CF mesh at the middle bundle in the width. Data acquisition was performed at a frequency of 1Hz.

The static tests were performed under displacement control at a loading rate of 0.5 mm/min. While in the fatigue tests, the minimum and maximum loads were chosen to ensure the occurrence of fatigue failure. The minimum load was determined to prevent excessive movement of the specimens during dynamic loading. The maximum loads were chosen to represent the conditions exceeding the service load levels of the beams. A static load from 0 up to the fatigue maximum limit was applied at a loading rate of 12 kN/min; then, unloaded to 0. This step was repeated, but the load was unloaded to the middle value of maximum and minimum limit, and a sinusoidal fatigue load was subsequently applied at a loading frequency of 5 Hz. When the number of cycles reached some predetermined cycles, the machine was stopped and a static load from 0 to the fatigue maximum limit was applied at a loading rate of 12 kN/min. The minimum and maximum limit were set corresponding to the percentage of yielding capacity of Control-S beam that was around 183 kN (P_0) after testing. The minimum limit was 25 kN that corresponds to 14% of P_0. The maximum limit in Control-F and CF1-F beams was 133 kN that corresponds to 73% of P_0, while in CF2-F beam was 152 kN that corresponds to 83% of P_0, as listed in Table 3.

3. RESULTS AND DISCUSSIONS

3.1 Static Performance

The applied load-deflection performance of the tested RC beams is shown in Fig. 4. The static test results including experimental ultimate load, calculated flexure strength, and failure mode are listed in Table 4. The flexure strength of Control-S was calculated at steel yielding using bending theory, while the flexure strengths of CF1-S and CF2-S were calculated at CF rupture failure. The Control-S beam performing as a typical under-reinforced RC beam failed after steel yielding followed by concrete crushing at 206.4 kN. The failure mode is shown in Fig. 5(a). Noted that the experimental ultimate load was higher than the calculated flexure strength using bending theory, as shown in Table 4. The reason can be the support condition in which the horizontal displacement was unintentionally constrained. The additional axial load in both beam end support was generated due to the unintentional constraint. This constraint effect became more apparent after the yielding of tension reinforcement since the horizontal movement at support would become large after the yielding. Noted that this constraint was removed for all other specimens.

Since the flexural strength of Control-S was increased due to unexpected constraint at the support, the enhancement of the ultimate load capacity cannot be seen with CF1-S beam as shown in Fig. 4. However, in comparison of the yielding capacity as listed in Table 4, CF1-S beam increased to 197.3 kN due to strengthening with one layer of CF embedded into Carbon-FRCM. Partial fibers only bonded with matrix ruptured followed by the slippage in the core of fiber which leads to the loss of composite action. This is represented by the sudden drop in applied load, as shown in Fig. 4. As the applied load increased, an excessive slippage was observed until failure, as shown in Fig. 5(b). The usage ratio is defined as the force taken by CF at Carbon-FRCM plate failure divided by the tensile force of CF which given as Eq (1). The contribution to the load-carrying capacity from CF was calculated by the ultimate load in strengthened beams minus the yielding load in un-strengthened beam based on the experimental results in the paper. The tested force taken by CF at failure can be obtained assuming the internal level arm of 0.9 times of beam height. The results of usage ratio are also listed in Table 4. The usage ratio of carbon fabric as slippage happened was only around 30% compared to the tensile strength of fabric. The similar results can be found in [11] where this value was about 21.7% at fabric slippage failure.

$\psi = F_{f,test} / (A_f f_{fu})$ (1)

where,

ψ : usage ratio of carbon fabric

$F_{f,test}$: tested force taken by CF at Carbon-FRCM plate failure

A_f : cross-sectional area of CF

f_{fu} : tensile strength of CF

On the other hand, it can be observed from Fig. 4 that the RC beam strengthened by the precast Carbon-FRCM plate with two layers of CF mesh had a significant increasing on the ultimate load capacity compared to Control-S. The ultimate load capacity of CF2-S was 252.9 kN increasing 22.5% compared to Control-S. The failure mode of CF2-S is shown in Fig. 5(c) which was the concrete cover separation initiating from the end of precast Carbon-FRCM plate at one side of support. An obvious drop occurs after the ultimate load capacity for CF2-S that represents the rapid propagation of separation in concrete cover. The calculated flexure strength at flexural failure is larger than the experimental results at concrete cover separation failure, as shown in Table 4. The usage ratio of carbon fabric was about 48.3% compared to the tensile strength of fabric. It is evident that usage ratio of fabric in Carbon-FRCM plate should be improved further. In addition, the calculated failure capacity at concrete cover separation using concrete tooth model in [12] was much less than the experimental results. The possible reason is that the interfacial bond stress between reinforcement and matrix in the FRCM overlay was much less in this study due to the fabric slippage than that in the previous study [12]. These assumptions may lead to significant prediction errors. Therefore, further research in FRCM strengthening system is needed to provide reasonable and accurate model for predicting failure load at concrete cover separation.

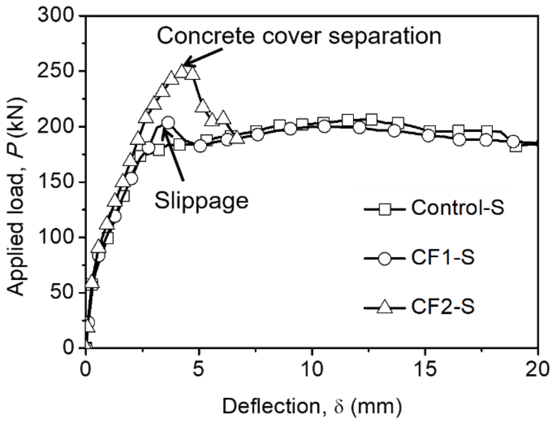


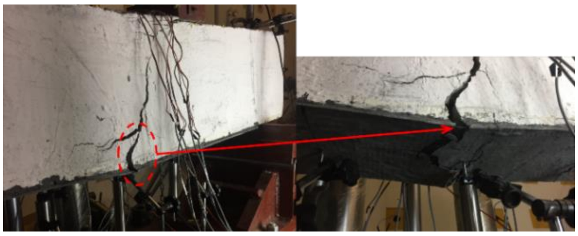
Fig. 4 Applied load-deflection relationship

Table 4. Summary of the static test results

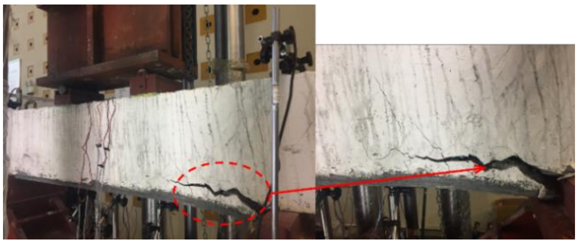
ID	$P_{y,exp}$ (kN)	$P_{u,exp}$ (kN)	$P_{u,cal}$ (kN)	ψ (%)	Failure mode
Control-S	183.0	206.4	137.6	N/A	CC
CF1-S	197.3	204.6	211.1	30	S
CF2-S	236.1	252.9	279.4	48.3	CCS

Note: CC = steel yielding followed by the concrete crushing at the top concrete; S = slippage and partial rupture of carbon fiber through the paste matrix; CCS = concrete cover separation from one end of Carbon-FRCM plate.

(a) Control-S



(b) CF1-S



(c) CF2-S

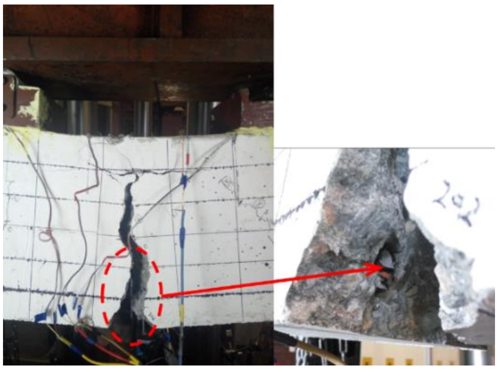
Fig. 5 Tested RC beams failure modes

3.2 Fatigue Performance

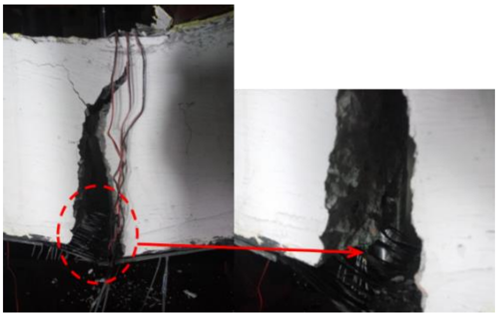
3.2.1 Fatigue life and failure modes

The results of fatigue life (cycles number) after testing is showed in Table 5. An evident extension on fatigue life can be observed due to strengthening with precast Carbon-FRCM plate. Fatigue failure happened after around 175,000 cycles for Control-F beam. The cycles increased up to 513,000 in CF1-F beam which is 1.9 times extension compared to Control-F. For strengthening with precast Carbon-FRCM plate containing two layers of CF mesh, the cycles can reach at 616,000 which is 2.5 times compared to Control-F beam fatigue life. This improvement can be attributed to the presence of precast Carbon-FRCM plate, which reduced the stress level in the tension steel reinforcing bars. It is concluded that the use of precast Carbon-FRCM plate is effective in prolonging fatigue life of RC beams.

Fig. 6 presents photographs of failure modes of un-strengthened and strengthened beams suffering from fatigue loading. The characteristic failure mode of Control-F was the steel reinforcing bar fracture in the vicinity of flexure crack at midspan. Similarly, the reinforcing bar fractured in CF1-F and CF2-F beams, where the excessive slippage of CF mesh from paste matrix was triggered subsequently. All beams failed by steel rupture, which indicates that the governing factor for the fatigue life of beams was the fatigue properties of the steel reinforcing bars in tension [13].



(a) Control-F



(b) CF1-F

Fig. 6 Failure modes of tested beams after fatigue loading

Consequently, based on the Standard Specification for Concrete Structures in JSCE, the fatigue strength of a deformed bar may be obtained using Eq. (2) and (3) as a function of a fatigue life. The material factor was not considered in the calculation. The experimental fatigue strengths based on the steel strain measured were 413 MPa, 238 MPa, and 239 MPa in Control-F, CF1-F, and CF2-F beams, respectively. Similarly, the calculated fatigue strengths of steel from bending theory were 398 MPa, 358 MPa, and 390 MPa in counterpart. It is evident that the predicted fatigue life based on measured steel strain of CF1-F and CF2-F were comparable to the experimental results. The calculated fatigue life in CF1-F is slightly higher than that in CF2-F which resulted from different load ranges in both beams. However, unexpected comparison results were obtained in calculated fatigue life from bending theory in which the fatigue life was underestimated. It is concluded that improvement on the prediction of fatigue life of un-strengthened and strengthened beams needs to be conducted.

$$f_{srd} = 190\,(10^{a} / N^{k})\,(1 - \sigma_{sp} / f_{ud}) / \gamma_{s} \qquad (2)$$

$$a = k_{0f}\,(0.81 - 0.003\,\phi) \qquad (3)$$

where,

f_{srd} : design fatigue strength
f_{ud} : design tensile strength of a deformed bar
γ_s : material factor of reinforcing bar
σ_{sp} : stress in reinforcing bar due to permanent load
N : fatigue life
ϕ : diameter of the reinforcing bar
k_{0f} : a factor depending on steel shape and generally be taken as 1.0
k : 0.12

Table 5. Comparisons of the fatigue life

ID	L_{exp} ($\times 10^3$)	L_{cal-1} ($\times 10^3$)	L_{cal-2} ($\times 10^3$)
Control-F	175	3.9	1.4
CF1-F	513	391	4.0
CF2-F	616	377	2.3

Note: L_{exp} = fatigue life recorded in the experiments; L_{cal-1} = calculated fatigue life based on JSCE in which the stress in steel was obtained from experiments; L_{cal-2} = calculated fatigue life based on JSCE in which the stress in steel was obtained by bending theory.

3.2.2 Discussions on the change of deflection

The change of deflection at midspan of beam with the increase of cycles for CF1-F and CF2-F beams is showed in Fig. 7. An initial substantial deflection can be produced at setting the maximum and minimum limit value. The comparative stable stage followed where the change on the deflection was minimal. However, the other significant stage occurred just before failure in which a substantial deflection increase can be observed. A little gradual increase in deflection was observed before reaching at approximate 400,000 cycles, as shown in Fig. 7. Subsequently, the deflection in CF1-F increased from about 1.25 mm to 1.6 mm after 500,000 cycles, and the beam failed at 513,000 cycles. Similarly, CF2-F beam's deflection increased from around 1.52 mm to 1.8 mm at 600,000 cycles, and this beam failed at 616,000 cycles. It is concluded that the importance and significance in monitoring deflections must be considered so that the fatigue failure can be foreseen.

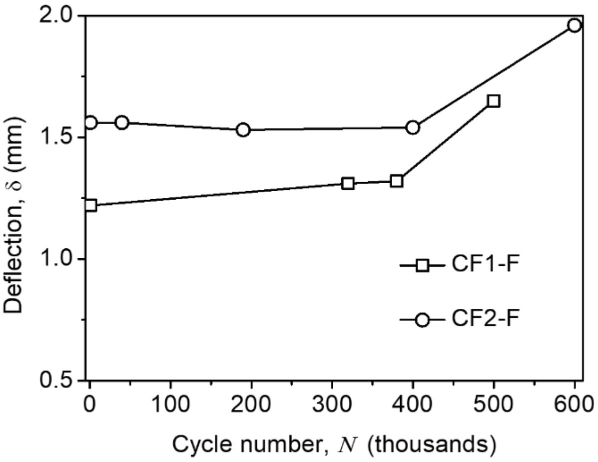


Fig. 7 Change of deflection at midspan with the increase of cycles

4. CONCLUSIONS

(1) The method using precast Carbon-FRCM plate composite has been proven to be effective in strengthening on the yielding capacity and ultimate capacity, in which the enhancement was mainly dependent on the layers of CF mesh.

(2) The failure modes of precast Carbon-FRCM strengthened RC beams were associated with the layers of CF mesh, where slippage failure occurred for one layer of CF mesh and concrete cover separation failure occurred for two layers of CF mesh.

(3) The new model is needed for predicting failure load at cover separation since the existing model is derived from the case in which there is good bond between externally bonded reinforcement and substrate concrete.

(4) The use of precast Carbon-FRCM plate in extending fatigue life of RC beams was viable that 1.9 and 2.5 times extension can be obtained in CF1-F and CF2-F beams respectively compared to Control-F beam.

(5) Fatigue properties of steel reinforcing bars in tension is the mainly governing factor on the fatigue life for both un-strengthened beam and precast Carbon-FRCM strengthened beams.

(6) The prediction of fatigue life of un-strengthened and strengthened beams exhibited conservative using the prediction method of bare steel bar.

(7) It is important to detect the symptom of beams' fatigue failure by monitoring deflections at a critical cross section.

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