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Fatigue performance of CFRP strengthened reinforced concrete bridge deck overhang

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ABSTRACT: After bonding CFRP for strengthening reinforced concrete bridge deck cantilever, an experiment for fatigue performance was performed in laboratory after putting high temperature of SMA paving overlay. The development of cracks, deflection, cross-sectional stresses and strains of materials were analyzed. The results indicated: (1) After the high temperature of SMA paving, the fatigue strength, stiffness, cracks resistance, ultimate bearing capacity of bonding CFRP reinforced beam is superior to the unstrengthened beam. (2) The ultimate bearing capacity is increased by 26.1%, the stiffness is increased by 22.8%, and the mean maximum width of crack is reduced by 19.1%.

1 INTRODUCTION

CFRP (Carbon Fiber Reinforced Polymer)[1] was used extensively for repair and rehabilitation because of the advantages, such as light weight, high tensile strength, noncorrosive, good durability and ease of installation techniques. The current research are primary focusing on using CFRP to strengthen the bottom or web of beams or concrete girders, but rarely involved in the deck strengthened by bonding CFRP plate[2]. A method of vertically inserting CFRP to near surface of bridge deck overhang was using on RÊslautal Bridge by Blaschko[3] to improve the bearing capacity. CFRP plate was bonded as rebar near the deck surface of bridge overhang, in vertical direction instead of parallel direction, to improve the ultimate bearing capacity with the increasing weight limit of traffic. And the monitoring shows that: The strengthened CFRP maintain an effective reinforced strength. An experimental investigation which explores the change in structural response due to the addition of near-surface-mounted (NSM) carbon fiber reinforced polymer (CFRP) reinforcement for increasing the capacity of the edge region of a reinforced concrete bridge deck was conducted by Anna[4]. The ultimate load carrying capacity of the FRP rehabilitated specimen was 196 kN, which was 78% higher than the ultimate load of the as- built specimen of 114 kN. With consideration of the minimal disruption to traffic flow and ease of installation, this system is viable and very attractive rehabilitation option for bridge deck slab overhangs. In order to strengthen Haversham Bridge[5] to meet the new 40 Tonne EC weight limit which proposed by European Union on 1st January 1999, a method of bonding CFRP to bridge deck was adopted on Haversham Bridge, which was the first time of bonding CFRP to bridge deck in Britain, and total 768m CFRP was applied. Later, carbon fiber plates were applied to top surfaces of Adur Viaduct on the A27 in Sussex to increase transverse bending capacity.

Above-mentioned experiments/projects investigated or explored only the static force of CFRP strengthening the bridge deck, but rarely on dynamics of structural especially the fatigue performance. The study of fatigue performance for bonding CFRP to the surface of bridge deck overhang is still a new issue throughout the world.

The Bangabandhu Bridge (also named as Jamuna Multipurpose Bridge) is located in Jamuna of Bangladesh, over the Jamuna River. And it is the only bridge that connects the east of Bangladesh to the west. The weather there is damp, hot, rainy, and there is no wearing course over bridge deck when open to the traffic. Due to the temperature stress, shrinkage and creep of concrete, numerous longitude cracks are visible on the surface of the bridge deck upon overhang side, and the amounts, length and width of the cracks are increasing with the passing of time. In order to repair the cracks, epoxy injection was used to repair the exist cracks, and high modulus CFRP was applied across the longitude cracks to restrain the farther development of cracks, and epoxy slurry was applied to level the surface, as last, 50mm thick SMA13 wearing course was provided. In view of there is no similar composite structure (CFRP + Epoxy Slurry + SMA) in engineering practice, and no investigation or research either, the fatigue test of CFRP strengthened beam in Lab. to simulate the new composite structure was carried out, to study the fatigue performance of CFRP strengthened overhang deck after going through the effect of high temperature.

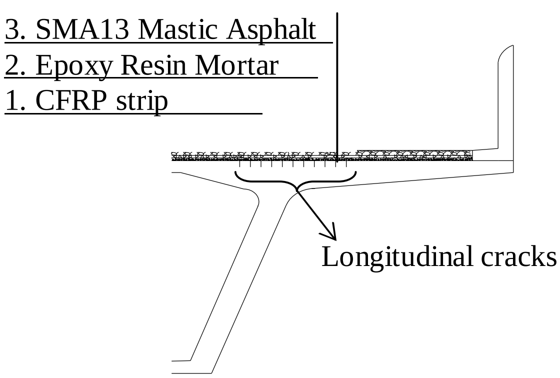
Figure 1. Bangabandhu bridge

Figure 2. Longitudinal cracks upon bridge deck-overhang

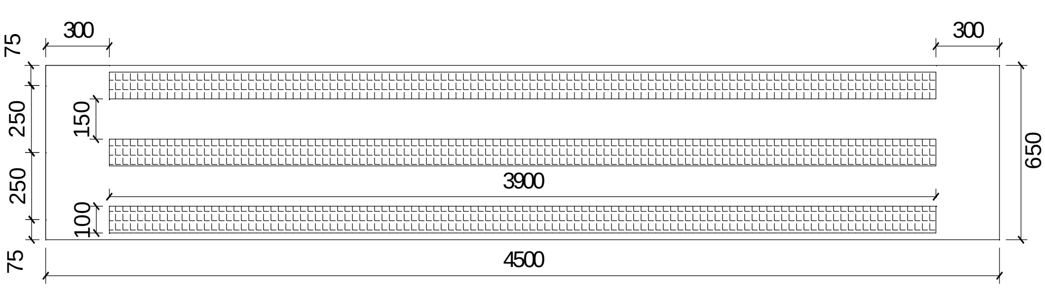
2 DESIGN OF CFRP STRENGTHENED BEAM

The width of Bangabandhu bridge deck is 18.5 m, two-way-four-line lane with a railway on the north side. The length of overhang on the south side of bridge is 3.95 m which in the tension zone of the negative bending moment. In view of the 280 mm thick of the bridge deck, the dimension of strengthened beam is 4000 mm×650 mm×280 mm, 3 strips of CFRP bond to the beam in the gap of 150 mm to simulate the design for Bangabandhu bridge.

The CFRP strip is 1.4mm thick and 100 mm width, with the tensile strength is 3015 MPa, E-modulus is 206 GPa, and elongation at break is 1.75%. The properties of epoxy adhesive for CFRP are: tensile strength is 45.5 MPa, modulus is 3.9 GPa, bend strength is 65.1MPa, and compressive strength is 94.5 MPa. According to the design for Bangabandhu bridge, the concrete is 45N, and the diameter of reinforced rebar is 18 mm belong to 55C, after the application of epoxy slurry, 50mm thick SMA wearing course was provided (as shown in figure 3). Both CFRP strengthened beam (CSB-1) and unstrengthened beam (CB-1) were tested.



(a) Design of repair for overhang deck



(b) Design of CFRP strengthened beam in Lab.

Figure 3. Design of overhang deck repair and experiment

3 FATIGUE TEST

Fatigue test was conducted on the electo-hydraulic servo-controlled fatigue testing machine. At first, calculate the ultimate bearing capacity of CSB-1 and CB-1, and then carry out the static force test in 10 grade of load computed theoretically, in order to ensure the Ultimate bearing moment M. Take M_{max}=0.527M as the limit of fatigue bearing. Maximum 2×10^6 times of fatigue load were applied with the frequency is 3Hz [6]. The loading program is: (i) Apply static force: To apply load from 0 to P^f_{max} (the upper limit of fatigue test) by different grade, the deflection and strain of midspan was recorded under every grade of load, then unload to 0. (ii) Apply fatigue force: increase the amplitude to enlarge the gap of crest and trough of load, to apply the fatigue load, then stop to apply static force when the loading times are 5000, 10^4, 2×10^4, 5×10^5, 5×10^5, 7.5×10^5, 10×10^5, 13×10^5 , 15×10^5 , 20×10^5. The data of cracking, ultimate load, width of cracks and deflection of midspan were recorded after every time unloading. Figure 4 shows the fatigue testing machine.

Figure 4. Load device of fatigue experiment

3.1 *Development of Cracks*

To observe the occurring and development of cracks, and record the width in microscope at 20x magnification, figure 5 shows the distribution of beam after fatigue load[7]. In the profiles, the width of cracks are increase rapidly at initial stage under every grade of load, and became slowly with the going of loading times, the width of cracks are larger under higher load. The maximum width of concrete for a CSB-1 is 0.28mm, under the load of 120kN, when undergoes 2×10^6 times of fatigue load. In the midspan of beam where the bearing moment is high, cracks occurred earlier and often developed in these places when a higher load applied.

Due to the constraint of CFRP, the cracks development of CSB-1 is slower versus to CB-1, and the cracks nearly closed when unload. The gaps of cracks are small but with more amounts. The amount of cracks increase more slowly at later period and nearly no grows after 2×10^6 times of fatigue load.

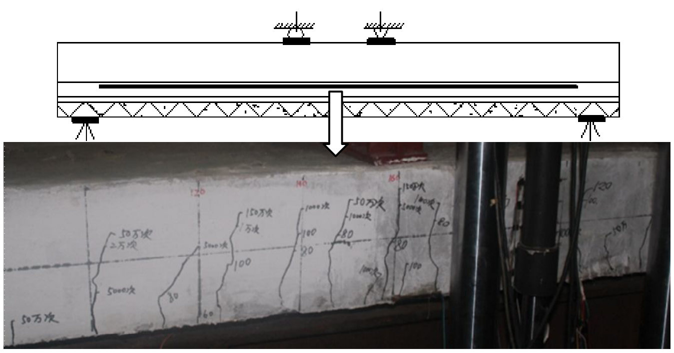


Figure 5. Development of cracks

The maximum mean cracks width of CSB-1 is 0.28mm (As shown in Figure 6), which is about 19.1% decrease to the width of 0.346 mm for CB-1, indicated that there is improve in fatigue life with the strengthen of CFRP. Because of the using of CFRP, cracks were restrained and the cracks resistance capability was improved, which will reduce the risk of cracking on the deck surface upon overhang under ultimate load.

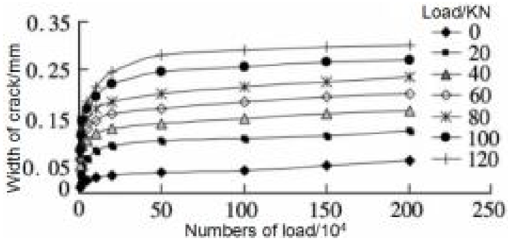


Figure 6. Cracks-Numbers of load curve with evaluated load

3.2 *Deflection*

Setting dial indicator at the mid-span and bearing to measure the deflection of beams. The deflection of CSB-1 is smaller than CB-1. As figure 7 shows, the deflection increase rapidly at initial stage, slowly at later period. The deflection of CSB-1 is nearly no growing after 2×10^6 times of fatigue load, and the maximum mean deflection reaches 10.83mm under the load of 120kN, which is 17.5% reduce versus to CB-1, and the fatigue strength is increase of 22.8%. The results indicated that after the impact of high temperature caused by SMA paving, the CFRP work together with concrete beam and is able to restrain the increasing deflection at midspan under the growing loads.

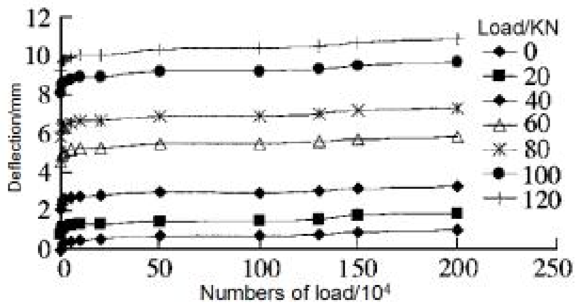


Figure 7. Deflection-Numbers of load curve with elevated load

3.3 *Strain of Rebar*

Strain gage was setting on the rebar of mid-span to measure the strain of rebar during test. The load-strain curves shown in figure indicated that the strains of rebar increase slowly at initial stage and rapidly at later period, with the increasing of load. The strains grow with the numbers of load increasing. Due to the restraint of CFRP, the strains of rebar for CSB-1 were smaller than CB-1 under the same load, and CSB-1 is able to undertake more load when the strains of rebar equal to CB-1.

When unload to zero, there are residual strains in CFRP strengthened beam, which mainly undertook by rebar, and there is no stress in CFRP. As the load increasing, cracks occurred at the bottom of mid-span, at the same time deformations and stresses in CFRP become growing rapidly. Under the load of 120KN, the maximum mean strain of rebar for CSB-1 is 1.575×10^{-3} (as shown in figure 8) after 2×10^6 times fatigue load, which is lower than CB-1.

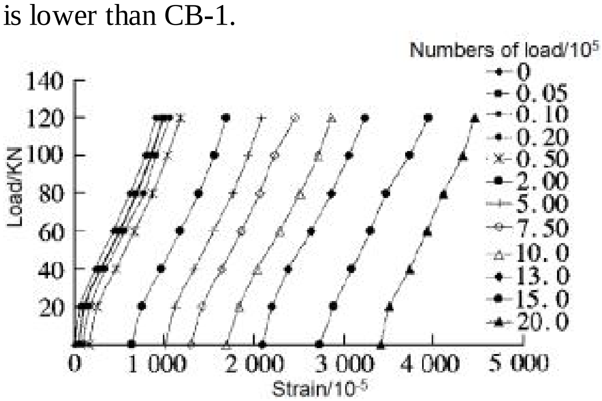


Figure 8. Load-Strain curves with elevated numbers of load for enforcement

3.4 *Strain of Concrete at Bottom of Beam*

After ten thousand times of fatigue load, strain curve of concrete become linear, indicated that the maximum mean strains of cross-section still conform to the plane cross-section assumption even after times of fatigue load[8]. The maximum mean concrete strain of CSB-1 is lower than CB-1, shows that even after high temperature action of SMA paving, CFRP is still able to mitigate the tension stress in concrete significant, and it means a lot to flexural-tensile failure of overhang deck[9].

3.5 *Strain of CFRP*

Strain gage is setting on CFRP at mid-span to measure the strains of CFRP during fatigue test, and figure 9 shows the mean strain of CFRP in the mid-span. The profiles show that the strain curves of CFRP are straight linear, which means CFRP are under elastic stage[10]. And even after high temperature action of SMA paving, the increasing rate of CFRP strains almost stay the same with the increasing numbers of load under different load grade. The curves also indicate that CFRP maintain a good elastic condition even after high temperature impact of SMA paving.

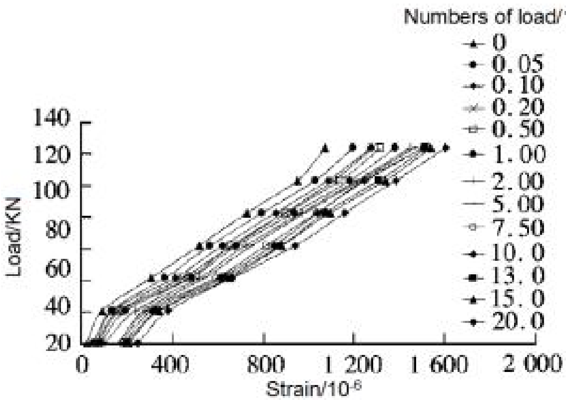


Figure 9. Load-Strain curves under elevated numbers of load for CFRP

4 FE ANALYSIS

CFRP was in contact with concrete by means of tie to create interaction, and the rebar were in contact with concrete by means of embed to create interaction. The degree of freedom of restraining plates in the spacer is U2, U3, UR1, to create hinged support. The load was applied every 10 KN on the spacer coupled to concrete. The FE model was shown as Figure 10.

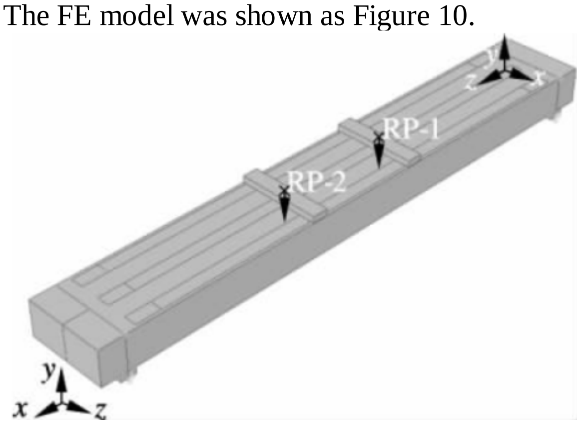


Figure 10. FE model of CFRP strengthened beam

The plane cross-section assumption is still work under the fatigue load. The stresses of rebar and concrete are far below their yield strength. Base on elastic theory, assume the stress of adhesive along the thick direction is constant, and consider the impact of shear deformation of the reinforced beam, setting the origin of x coordinates is located at the endpoint of mid-plane of the adhesive, and the normal stress[11] of bonding interface σ_x is able to be calculated by the following formula:

$$\sigma_x = e^{-\eta x}\left\{\frac{E_{ep}}{4\eta^3 t_{ep}}\left[\frac{(s(s+b_1)\eta + b_1)q}{E_c I_c} + \frac{2\alpha_s \eta q}{G_c t_c} + \left(\frac{t_p}{E_p I_p} - \frac{t_c}{E_c I_c}\right)\tau(0)\right]\cos\eta x - \frac{qE_{ep}}{2\eta^2 t_{ep}}\left(\frac{s}{2E_c I_c}(s+b_1) + \frac{\alpha_s}{G_c t_c}\right)\sin\eta x\right\} + \frac{t_p - r_{pc} t_c}{2(1+r_{pc})}\frac{d\tau(x)}{dx} - \frac{r_{pc}}{1+r_{pc}}q(x)$$

$$\frac{d\tau(x)}{dx} = -\frac{qG_{ep}}{2t_{ep}}\left\{\left[\frac{s(s+b_1)t_c}{2E_c I_c} + \frac{\alpha_s}{G_c} - \frac{\alpha_{E_c}(t_c+t_p)}{\beta^2 E_c I_c}\right]e^{-\beta x} + \frac{\alpha_{E_c}(t_c+t_p)}{\beta^2 E_c I_c}\right\}$$

$$= \frac{qG_{ep}}{2t_{ep}\beta}\left\{\left[\frac{s(s+b_1)t_c}{2E_c I_c} + \frac{\alpha_s}{G_c} \quad \frac{\alpha_{E_c}(t_c+t_p)}{\beta^2 E_c I_c}\right] + \frac{\alpha_{E_c}(t_c+t_p)}{\beta^2 E_c I_c}\right\}$$

$$\eta^4 = \frac{E_{ep}}{4t_{ep}}\left[\frac{1}{E_c I_c} + \frac{1}{E_p I_p}\right]$$

$$r_{pc} = \frac{E_p I_p}{E_c I_c}$$

Where, the subscript of *c, p, ep* stand for concrete beam, CFRP plate and adhesive respectively. E, I, G and t stand for E-Modulus, moment of inertia, Shear modulus and thickness. α_s is shearing factor, b_1 is the length of CFRP, s is the distance from the support to end of CFRP plate, q is the uniformly distributed load on one unit of width, α_{E_c} and α_{E_p} is the bending stiffness factor separately.

With the addition of strain of rebar in tensile region and compressive region as well as the fatigue circulation times, the upper limit & lower limit of deflection are increased. The results of FE analysis, theoretical calculation and experiment of ultimate bearing capacity under static force are shown in table 1.

Table 1. Data of ultimate bearing capacity under static force

No.	Test result /KN.M	Calculation / KN.M	Deviation with test result / %	FE result / KN.M	Deviation with test result / %
CSB--1	159.60	150.18	-5.90	154.00	-3.51
CB-1	198.82	187.31	-5.79	192.00	-3.43

The ultimate bearing capacity under static force of CSB-1 is 24.6% higher than the CB-1, even after the high temperature impact of SMA paving. The fatigue strength of CSB-1 was calculated by the method of analytical stiffness, and table 2 show results from analytical stiffness method and experiment. The data indicates that the experiment result is well consistent with the theoretical computation result.

Table 2. Data of fatigue strength from analytical stiffness method and experiment.

Numbers of load/10^4	Theoretical result	Test result
1	1.83	1.84
10	1.79	1.82
30	1.75	1.79
50	1.69	1.75
100	1.63	1.71
150	1.54	1.62
200	1.46	1.53

5 CONCLUDING REMARKS

After the high temperature installation of SMA paving, the ultimate bearing capacity of CSB-1 under static force is increase by 26.1% compared to CB-1, the maximum mean deflection is decrease by 17.5%, and the fatigue strength is increase by 22.8%.

Even after the high temperature impact of SMA paving, CSB-1 didn't broken after 2×10^6 times fatigue loads. The amount of cracks increase more slowly at later period, and the maximum mean cracks width decrease by about 19.1% when compare to CB-1, which means CFRP strengthen overhang of bridge deck is an effective method to restrain the cracks.

The concrete strain of CSB-1 is lower than CB-1, shows that even after high temperature impact of SMA paving, CFRP is still able to mitigate the tension stress of concrete significantly, and improve the ultimate bearing capacity of bridge deck overhang after the fatigue load.

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