Moving-Wheel Load Test of a Cantilevered RC Slab Strengthened with Bond-Improved Ultra-High Modulus CFRP Rods

Hiroaki Hasegawa, Takahisa Kato, Kodai Shimose, and Isamu Yoshitake

1 Introduction

Fatigue is a serious concern for bridge deck slabs directly subjected to wheel load. Heavy traffic load and de-icing materials significantly accelerates fatigue damage of the slab. In particular, cantilevered deck slabs under negative bending moment have been remarkably damaged. Near-Surface-Mounted (NSM) is an effective strengthening method for concrete members under fatigue loading (Teng et al. 2001; Yoshitake et al. 2010; Dongkeun et al. 2011). This study focuses on the NSM strengthening method using a Carbon Fiber Reinforced Polymer (CFRP) rod of ultra-high modulus and a polymer-cementitious mortar of ultra-high-early strength. The greatest concern in the NSM strengthening is the significant low-bonding property of the CFRP rod embedded in the mortar. Our previous study developed a bond-improved CFRP rod attaching Glass Fiber Reinforced Polymer (GFRP) ribs and conducted monotonic and cyclic loading tests of RC beams strengthened with the bond-improved CFRP rods (Hasegawa et al. 2016; Kuroda et al. 2016; Hasegawa et al. 2018; Hasegawa et al. 2019; Yoshitake et al. 2020). The flexural loading test showed excellent fatigue durability of the beams. This study conducted a moving-wheel load test to confirm

H. Hasegawa · T. Kato
Mitsubishi Chemical Infratec Co., Ltd, Chuo-ku, Tokyo, Japan
e-mail: hasegawa.hiroaki.ms@m-chemical.co.jp

T. Kato
e-mail: kato.takahisa.ma@m-chemical.co.jp

K. Shimose · I. Yoshitake (✉)
Yamaguchi University, Tokiwadai, Ube, Yamaguchi, Japan
e-mail: yositake@yamaguchi-u.ac.jp

K. Shimose
e-mail: ShimoseKodai@yucivil.onmicrosoft.com

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Table 1 Material properties

	Nominal diameter	Cross-sectional area	Strength	Young's modulus
	mm	mm^2	MPa	GPa
Concrete	–	–	29.5[*a]	32.45
Mortar	–	–	55.9[*a]	30.84
Steel bar	13	126.7	406[*b]	206
CFRP rod	8	50.3	1386[*c]	440

[*]a: compressive strength, *b: yield strength, *c: tensile strength

the fatigue durability of the strengthened deck slab. The present paper reports the fatigue property of the slab.

2 Moving-Wheel Loading Test

2.1 Materials

Table 1 shows the material properties used in this study. Compressive strength and Young's modulus of concrete at 28 days were 29.5 MPa, 32.5 GPa, respectively. The strength of the polymer-cementitious mortar was significantly higher than the concrete strength. The compressive strength and Young's modulus of the mortar at 28 days were 55.9 MPa, 30.8 GPa, respectively. The modulus of the mortar was slightly lower than the modulus of concrete to reduce the interfacial shear stress. Young's modulus of CFRP rod of 8 mm diameter was 440 GPa. The modulus is 2.1 times higher than the modulus of steel reinforcement. The ultra-high modulus CFRP rod must contribute to the reduction of the rebar stress and the deflection of deck slab. Note is that the CFRP rod indicates low bond strength because of smooth surface. To improve the bond strength in concrete, the CFRP rods were wrapped with GFRP prepreg sheets to add the shear-resistance ribs (Fig. 1a). Dimensions of GFRP ribs were 1.5 mm thick, 75 mm long, 300 mm interval (Fig. 1b).

2.2 Cantilevered Slab Specimen

Figure 2 shows the preparation process of the cantilevered slab specimen strengthened with CFRP rods. A RC slab of 140 mm thick was firstly made and thin concrete-cover of top surface was removed by using water-jet (Fig. 2a). The top surface was coated with epoxy resin at the concrete age of 58 days (Fig. 2b). The polymer-cementitious mortar of 20 mm thick was cast on the fresh epoxy resin. The bond-improved CFRP rods were embedded in the mortar (Fig. 2c). The embedment depth

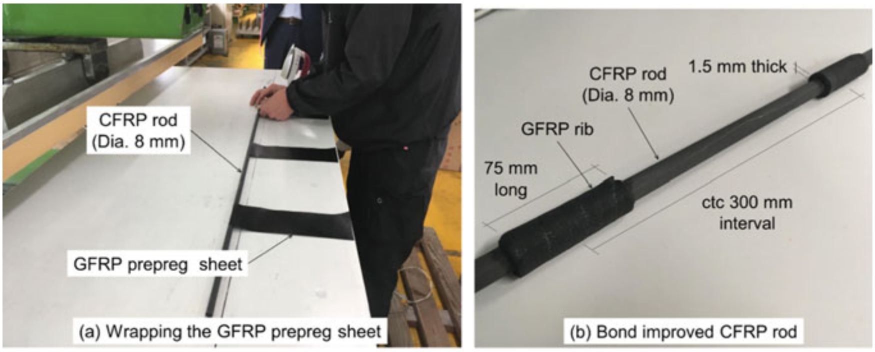

Fig. 1 Bond-improved CFRP rod

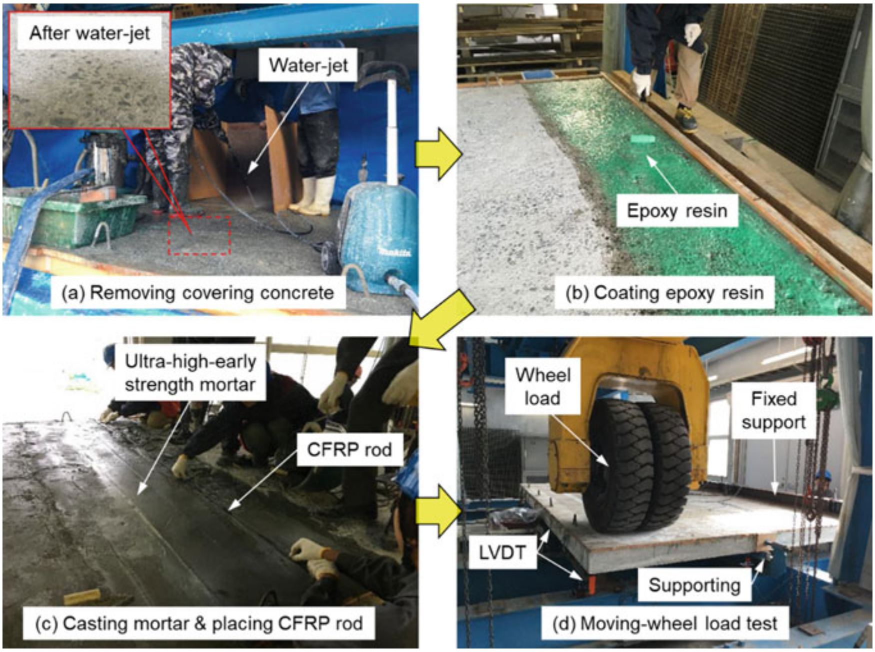

Fig. 2 Process flow of the specimen preparation

of CFRP rod was approximately 15 mm. Figure 2d shows the moving-wheel load of two solid rubber tires.

2.3 Experimental Procedure

Figure 3 shows the schematic of RC slab specimen. Dimensions of the specimen were 3050 mm width, 4500 mm long, 160 mm thick. The CFRP rods (Dia. 8 mm) and main rebars (SD345 D13) intervals (center to center) were 200 mm, 150 mm respectively. The slab end was fixed with a H-steel of 150 mm height and PC bars of 13 mm diameter. The cantilevered slab was supported on a rigid steel bar of 50 mm diameter which was placed at 1600 mm from the fixed edge. The cantilevered span was 1000 mm. The moving span of wheel load was 3600 mm. The wheel load of 60 kN was applied on the slab specimen up to 1,000,000 cycles. After that, the increased load of 70 kN was applied up to 120,000 cycles. The maximum stress of the rebar was calculated as 210 MPa under the loading of 60 kN. The stress is 1.5 times higher than the allowable stress under the service load (Japan Road Association 2017). The strains of CFRP rod and reinforcing bar and the free-end deflection were monitored during the moving-wheel load test (Fig. 3).

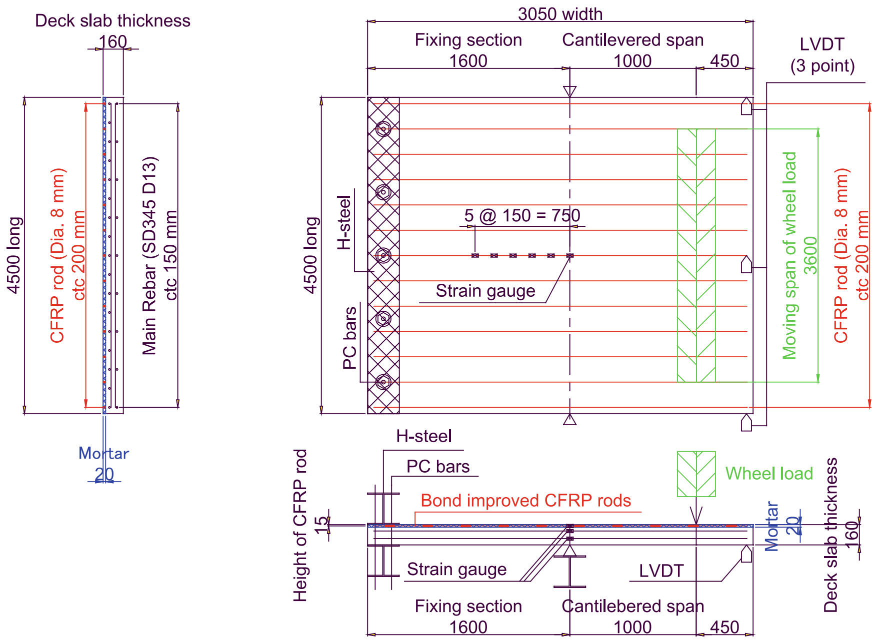

Fig. 3 Schematic of specimen

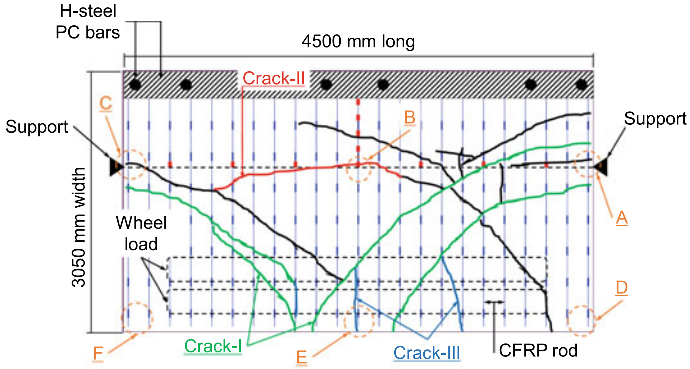

Fig. 4 Crack pattern after 1,120,000 wheel-loads

3 Test Results and Discussion

3.1 Cracking Behavior

Figure 4 shows the crack pattern of specimen subjected to 1,120,000 wheel-loads (1,000,000 cycles for 60 kN + 120,000 cycles for 70 kN). When the wheel load was applied on the slab end (D/F), the cantilevered slab was subjected to the maximum moment. Crack-I (A – E and C – E) occurred due to the maximum bending moment until 1,000 cycles. A longitudinal crack (Crack-II) at the support occurred and developed from 100,000 to 150,000 loading cycles because the flexural rigidity of the cantilevered slab decreased by the flexural cracks (Crack-I). The transverse crack (Crack-III) occurred up to 600,000 cycles. After that, remarkable cracks were hardly observed until 1,120,000 cycles.

3.2 Estimation of Equivalent Loading Cycles

The moving-wheel load test had been conducted to estimate the fatigue durability of bridge deck slabs. Maeda and Matsui (1984) reported that the moving-wheel load test could simulate the fatigue failure of the slab. Matsui (1991) proposed an empirical equation (Eq. 1) to estimate the fatigue life of RC deck slab based on the moving-wheel load test. Kaido and Matsui (2008) also reported that the fatigue durability of cantilevered steel–concrete composite slabs can be estimated by Eq. (1). The study assumed that Miner's linear rules are applicable for the fatigue damage accumulation. The equivalent cycles for the different loads can be calculated by using Eq. (2).

$$\log\left(\frac{P}{P_{sx}}\right) = -k \cdot \log N + \log C \tag{1}$$

$$n_{eq1} = \sum \left(\frac{P_i}{P}\right)^{\frac{1}{k}} \cdot n_i \quad (2)$$

where P is wheel load; P_{sx} is static loading capacity of the slab; k is coefficient (0.07835); N is the ultimate loading cycle; C is coefficient (1.23 for wet and 1.52 for dry); n_{eq1} is equivalent loading cycle and n_i is loading cycle.

Based on these assumptions, the loading history (1 million cycles for 60 kN + 120,000 cycles for 70 kN) was equivalent to 2 million cycles for the initial load of 60 kN. The cantilevered slab strengthened with NSM CFRP rods endured 2 million loading cycles even under the 150% higher wheel load than the service load (Japan Road Association 2017).

3.3 Deformation

Figure 5 shows the deflection at the free-end of the cantilevered slab (point E in Fig. 4). The deflection increased significantly due to the flexural cracking (Crack-II), and gradually increased after 150,000 cycles. Figure 5 also shows that the deflection slightly increased by the occurrence of Crack-III at 600,000 cycles.

Figure 6 shows the strains of rebar and CFRP at point B in Fig. 4. It presents remarkable increase of strain at 60,000 cycles. The strains increased gradually until 150,000 cycles. The observation implies that invisible flexural cracks occurred on the support. Note is that the invisible cracks had developed to the visible cracks (Crack-II) as increase of load cycles. After 150,000 cycles, there was no significant strain variation except for 600,000 cycles at that Crack-III was occurred. Figure 7 shows the strain distribution of CFRP. The CFRP strain at the support section increased significantly at 150,000 cycles. The CFRP strain at 300 mm from the support increased remarkably. The gradual increase of deflection from 150,000 to 600,000 cycles was caused by the cracking in the fixing section.

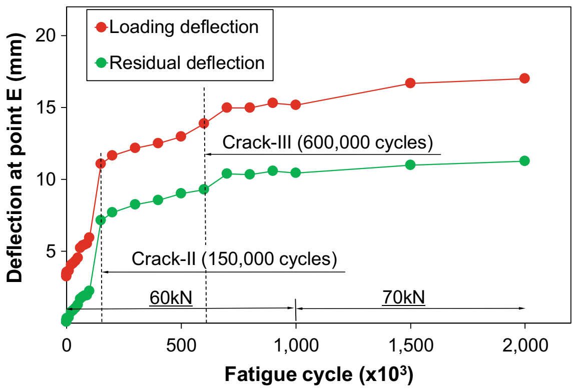

Fig. 5 Deflection—Fatigue cycle relation

Fig. 6 Strain—Fatigue cycle relation

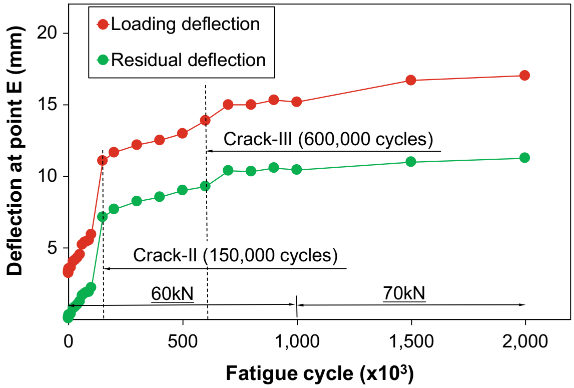

Fig. 7 Strain distribution of CFRP

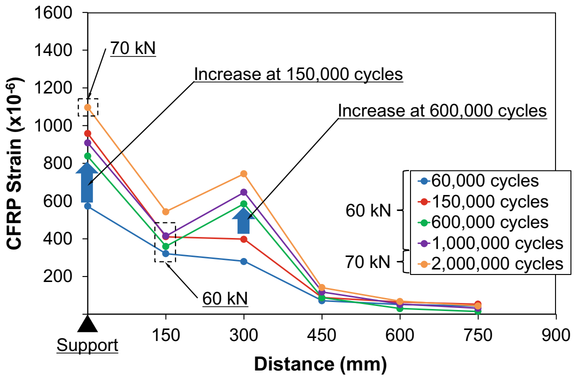

Fig. 8 Strain profiles

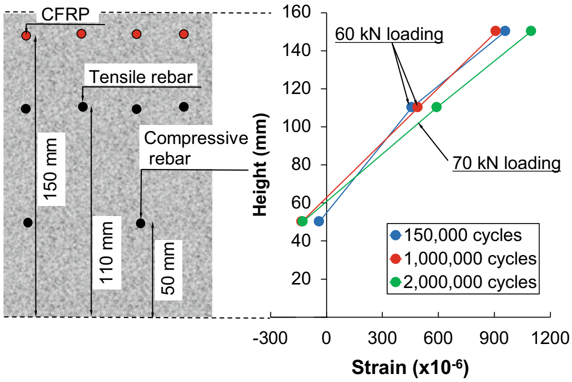

Figure 8 shows the strain profiles. The linear profiles imply that debonding or slippage of CFRP rods did not happen. The bond-improved CFRP rod with GFRP ribs indicated the adequate bond property up to equivalent 2 million wheel-loads of 60 kN.

4 Conclusions

This study focused on the fatigue durability of cantilevered RC deck slab strengthened with ultra-high modulus CFRP rods. The moving-wheel loading test of cantilevered deck slab was conducted to examine the fatigue properties. The conclusions of this study are as follows:

(1) The cantilevered RC slab strengthened with the bond-improved CFRP rods endured the equivalent 2 million wheel-loads of 60 kN that was 150% higher than the designed service load. The moving-wheel load test confirmed the adequate fatigue durability.
(2) The deflection and strain after 600,000 cycles were stable until 2 million cycles. The strain profile was linear up to the equivalent 2 million cycles. The observation confirmed that the CFRP rod with GFRP ribs had appropriate bond capacity even under the 2 million cycles of wheel load.

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