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Feasibility study on the fatigue characteristics of the reinforced CFS with self-healing repair methods for RC slabs

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Japan's Ministry of Land, Infrastructure, Transport and Tourism surveyed and inspected bridges with the goal of increasing the lifespan of the bridges and to downwardly standardize bridge maintenance costs, and established the "Highway Bridges Long Life Repair Plan." According to the results of survey and inspection, the most serious damage to RC slabs is caused by fatigue deterioration, which results from the driving loads of large-sized vehicles, and aging of materials. In response to this, adhesion reinforcement using carbon fiber sheet is being adopted. Therefore, in this study, specimens with bottom side CFS adhesion reinforcement on the bottom surface of the RC slab were manufactured. Then, fatigue tests under running wheel loads were conducted, and thus fatigue resistance was evaluated using the specimens. In addition, new RC slab supplementation technique was suggested.

Key words: RC slabs, Reinforcement, CFS, Self-healing repair methods.

Introduction

In recent years, Japanese local governments have started the "Highway Bridge Long Life Repair Plan" [1]. While implementing this undertaking, the portion of the bridge with the highest damage potential was found to be the RC front plane. The RC planes installed during the high economic growth period, exhibited inferior characteristics in terms of the design load, plane thickness, and rebar amount, failing to meet the standards and guidelines of the specifications for highway bridges [2].

On the other hand, the Highway Bridge Long Life Repair Plan established a maintenance and management plan aiming at achieving 100-year integrity after construction. This plan provides the framework for repair and reinforcement techniques for and estimation of the remaining service life and life cycle cost (LCC). Carbon fiber sheets (CFSs), which meet the repair standards of this plan, are attracting much attention for their efficacy in supplementing the rebar amount and RC plane thickness and recovering the load resistance and fatigue resistance of the RC planes [3, 4].

This study aims to evaluate the reinforcing effects and fatigue resistance of CFSs. The authors prepared two types of CFS specimens by applying the CFS adhesive backing technique and performed a fatigue test under a running wheel load. Additionally, drawing on the research results related to self-healing repair methods published in South Korea [5], we explored the feasibility of integrating self-healing repair methods to adhesive-backed CFSs.

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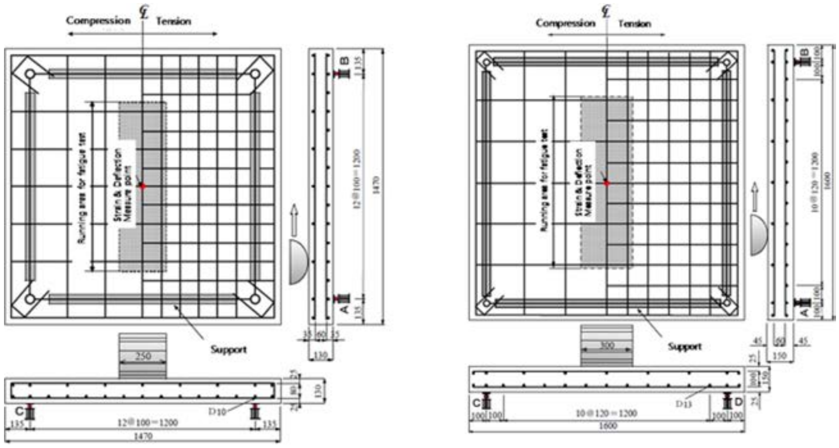
Experimental Procedure

Fabrication of Specimens

The specimens used in this test were designed based on Japan's Specifications for Highway Bridges [2] and modeled according to the wheel load of the tested equipment, that is, according to the ratio of vehicle wheel width to wheel load width (500mm) prescribed in the Specifications for Highway Bridges. In other words, a specimen with a wheel of which the width of the wheel load is 250 mm was used as a 1/2 model (= 250/500) and a specimen with a wheel of which the width of the wheel load is 300 mm was used as a 3/5 model (= 300/500). The 1/2 model specimen is called type A. And the 3/5 model specimen is called type B.

Materials

For the concrete in the type A specimen, ordinary Portland cement was used. In addition, crushed sand measuring 5 mm or less in size and crushed rock measuring 5 mm-20 mm in size (JIS A 5005) were used. The Specifications for Highway Bridges prescribe the



(a) Type A (b) Type B

Fig. 1. Specimen size and reinforcement arrangement.

Table 1. Mix proportions of concrete for RC slab.

Slump (cm)	W/C (%)	s/a	Unit Weight (kg/m^3)					Chemical Admixture (ml)
			C	W	S	G	SP	AE
18 ± 2.5	51.4	51.2	319	164	953	886	1.91	16

Table 2. Characteristic values of concrete and rebars.

Test Specimen	Compressive Strength Of concrete (N/mm^2)	Rebar (SD295A)			
		Diameter Of rebar	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young's Modulus (kN/mm^2)
Type A	35	D10	368	516	200
Type B	30	D13	370	511	200

design standard concrete strength for RC slabs of highway bridges as 24 N/mm^2 or higher. Therefore, the concrete of the type A specimen was mixed targeting a design strength of 24 N/mm^2 or higher (compression strength at test as 35 N/mm^2). For reinforcing bar, SD 295A, D10 was used in both specimen types.

Next, for concrete in the type B specimen, ordinary Portland cement crushed sand measuring 5 mm or less in size and crushed rock measuring 5mm - 20mm in size (JIS A 5005) were used as in the type A specimen. The concrete was mixed targeting a design strength of 24 N/mm^2 or higher (compression strength at test as 30 N/mm^2). For reinforcing bar, SD295 A, D13 was used.

Details of concrete mixing for specimens of all types are listed in Table 1, and concrete compression strengths during the fatigue test under a running wheel load and reinforcing bar material characteristics are listed in Table 2.

As for the CFS used in this test, a continuous fiber sheet with a unit weight of 200 g/m^2 and design thickness of 0.111 mm was used. In addition, primer to increase the strength of CFS adhesion to the RC slab and an adhesive exclusively developed for CFS were used. The CFS material characteristics are listed in Table 3.

Table 3. Mechanical properties of CFS.

Sheet Name	Unit Weight (g/m^2)	Thickness (mm)	Tensile Strength (N/mm^2)	Young's Modulus (kN/mm^2)
CFS	200	0.111	4,420	235

-Specimen dimensions and reinforcing bar arrangement

In case of type A, the dimensions of type A RC slab specimens are 1,470 mm in length, 1,200 mm in span and 130 mm in thickness. Reinforcing bars are laid out for double reinforcement. For the main reinforcement on the tension side (perpendicular to axis), D10 bars are laid out at an interval of 100 mm, and the valid height is set as 105 mm. As for traverse reinforcement (axial direction), D10 bars are also laid out at an interval

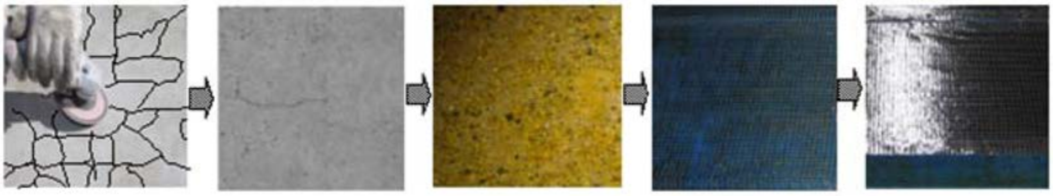


Fig. 2. Adhesion Process of Carbon Fiber Sheet (CFS).

of 100 mm and the valid height is set as 95 mm. Reinforcement on the compression side is allocated as 1/2 of the reinforcement on the tension side. The type A specimen with a concrete compression strength of 35 N/mm^2 is called A-RC. The dimensions of type A RC slab specimens and reinforcement arrangement s are shown in Fig. 1 (a).

In case of type B, the dimensions of type B RC slab specimen are 1,600 mm in length, 1,400 mm in span and 150 mm in thickness. Reinforcing bars are laid out for double reinforcement. For the main reinforcement on the tension side (perpendicular to axis), D13 bars are laid out at an angle of 120 mm, and the valid height is set as 125 mm. As for traverse reinforcement (axial direction), D13 bars are also laid out at an interval of 120 mm and the valid height is set as 112 mm. Reinforcement on the compression side is allocated as 1/2 of the reinforcement on the tension side.

The type B specimen with concrete compression strength of 30 N/mm^2 is called B-RC. The dimensions of type B specimen and reinforcement arrangement s are shown in Fig. 1(b).

CFS bottom side Adhesions

The CFS used in this test is high-strength tou sheet and high-strength strand sheet from Japan's Nippon Steel & Sumikin Materials Co., Ltd. [6]. Adhesion reinforcement using CFS is designed based on "Design and Construction Guidelines for Highway Bridge Concrete Material Repair and Reinforcement Using Carbon Fiber Sheet Adhesion Technique (draft)" [7] from Japan's Public Works Research Institute. The sequences of CFS bottom side adhesion reinforcement are shown in Fig. 2, respectively.

The scope of CFS bottom side adhesion reinforcement is 1,100 mm × 1,100 mm inside the area between the points of the specimens for type A specimens. For the type B specimen, bottom side adhesion reinforcement is carried out for 1,300 mm × 1,300 mm inside the area between the points. For CFS bottom side adhesion reinforcement, impurities are first removed from the bottom side of the RC slab and surface treatment is carried out for surface loss as shown in Fig. 2(a,b). Following surface treatment, primer coating and impregnation are carried out in order to increase CFS adhesion to the concrete part, and the structure is left to cure for over 12 hours as shown in Fig. 2(c). Then, CFS

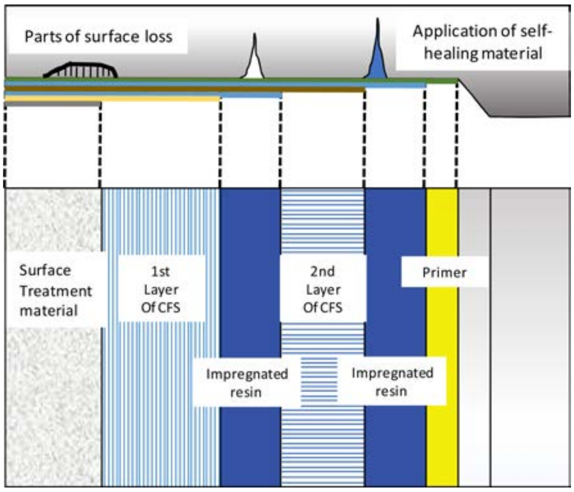


Fig. 3. The concept of application for self-healing repair methods.

measuring 500 mm in width is attached to the front of the slab in the direction of main reinforcement using epoxy-type impregnation resin developed exclusively for CFS, and the structure is left to cure for more than 12 hours as shown in Fig. 2(d). The second layer is attached at a right angle to the main reinforcement using the same method as shown in Fig. 2(e). The specimens with CFS bottom side adhesion reinforcement on the type A RC slab specimens are called A-CFS. In addition, the specimen with CFS bottom side adhesion reinforcement on the type B RC slab specimen is called B-CFS.

Application for self-healing repair methods

The CFS adhesive backing technique employs epoxy injection into cracks of widths ≤ 0.2 mm for local cross section rehabilitation in damaged sites. Effective methods for repairing post-reinforcement cracks and cracks with widths 0.2 mm, which are undetectable by visual inspection, are yet to be found. In this context, studies are required to develop an upgraded material capable of preventing water from leaking in through cracks by integrating the self-healing material with the currently used repair materials. In addition to applying these materials to micro cracks, it also makes the time-consuming epoxy injection redundant for crack repair. Fig. 3 shows a schematic of the hybrid method of using CFS adhesive backing and fabricating a coating of a self-healing material.

Fig. 4. Process of fatigue test under running wheel load equipment.

Results and Discussion

As shown in Fig. 4, this is a fatigue test under a running wheel load to evaluate the fatigue resistance of unreinforced RC slab, an RC slab with bottom side CFS adhesion reinforcement applied.

The equipment for the fatigue test under a running wheel load is manufactured by installing a forced wheel load on a forced reaction frame (400 kN) beam and fixing in a hydraulic vibration fatigue tester. Then, a cart installed with a specimen is oscillated in a horizontal direction through the connection of a motor and crank arm to recreate the driving state under wheel load.

For evaluation of reinforcement effect and fatigue resistance of an RC slab with CFS bottom side adhesion reinforcement through a fatigue test under a running wheel load, the load is increased by stages each time driving is completed 20,000 times. Therefore, evaluation is carried out by calculating the number of equivalent cycles from the test load in relation to base load and test cycles.

As for the base load for specimens of each type, a model with a wheel width of 250 mm was used in the fatigue test under a running wheel load on the type A specimens. Being a 1/2 model of the one with a T load width of 500 mm defined in the Specifications for Highway Bridges, the specimen was also created as a 1/2 model. Therefore, the base load of specimens was decided as 60 kn by applying a safety factor of 1.2 to 1/2 of active load 100 kN defined in the Specifications for Highway Bridges. In addition, the type B specimen was created as a 3/5 model of the one defined in the Specifications for Highway Bridges. Accordingly, the base load of the specimen was decided as 72 kN.

The driving scope for the wheel load of the type A specimens in this test is 900 mm. The driving scope for the wheel load of the type B specimen is 1,000 mm. For the type A specimen, the load was increased by 20 kN from 60 kN to 100 kN each time driving was completed 20,000 times. For the type B specimen, the load was increased by 20 kN each time driving was completed 20,000 times from the initial load of 100 kN to 140 kN. After the load exceeded 140 kN, the load was increased by 10kN each time driving was completed 20,000 times. Load increase and driving as such were repeated until the specimen was destroyed. In this test, the reinforcement effect is evaluated by calculating the number of equivalent cycles. Therefore, the initial load in the fatigue test under a running wheel load does not affect the number of equivalent cycles.

In the fatigue test under a running wheel load, the load is increased each time driving is completed 20,000 times. Therefore, reinforcement effect and fatigue resistance are evaluated by calculating the number of equivalent cycles (N_{eq}) from the base load, running load and the number of test cycles. Assuming that N_{eq}, the number of equivalent cycles under a running wheel load, follows the minor, it can be expressed with the formula below (Formula -1). In addition, for m, the reciprocal number of inclination of the S-N curve applied to Formula-1, 12.7 suggested by Matsui was applied [8].

$$N_{eq} = \sum_{i=1}^{n} (P_i/P)^m \times n_i \qquad (1)$$

N_{eq}: Number of equivalent cycles, Pi: load (kN), P: reference load (Type A: 60 kN, Type B: 72 kN), n_i: Number of experimental runs, m: inverse number of the slope of the S-N curve (12.7) [8]

The numbers of equivalent cycles for unreinforced RC slab, CFS bottom side adhesion reinforcement RC slab of type A and B specimens are listed in Table 4.-

In case of Type A, the numbers of equivalent cycles of A-RC-1 and 2, the RC slabs of type A with concrete compression strength of 35 N/mm^2, are 7.3×10^6 and 8.5×10^6, respectively. The average number of equivalent cycles is 7.9×10^6. As for A-CFS-1 and 2, the unreinforced type A RC slabs with CFS bottom side adhesion reinforcement applied, the numbers of equivalent cycles are 163.3×10^6 and 133.1×10^6, respectively, and their average number of equivalent cycles is 148.25×10^6. Therefore, compared to the numbers of equivalent cycles of B-RC-1 and 2, the unreinforced RC slabs, the reinforcement effect was found to be larger by 18.7 times.

In case of Type B, the number of equivalent cycles of type B RC slab with concrete compression strength of 30N/mm^2 is 11.23×10^6. The number of equivalent cycles of B-RC-2 is 14.39×106, and the average number of equivalent cycles is 12.81×10^6. As for B-CFS-1, the RC slab specimen with CFS bottom side adhesion reinforcement applied, the number of equivalent cycles is 258.12×10^6. The number of equivalent cycles of B-CFS-2 is 269.52×10^6, and the average number of equivalent cycles is 263.82×10^6. This indicates a reinforcement effect 20.6 times larger than that indicated by the average number of equivalent cycles

Table 4. Number of equivalent cycles and Reinforcement number of equivalent cycles.

Test Specimen		Load							Total number of equivalent cycle	Average number of equivalent cycle	Number of equivalent cycle ratio
		60 kN	80 kN	100 kN	110 kN	120 kN	140 kN	15 0kN			
A-RC-1	Number of experimental cycle		20,000	10,009						7,938,030	-
	Number of equivalent cycle		772,240	6,574,607					7,346,848		
A-RC-2	Number of experimental cycle		20,000	11,809							
	Number of equivalent cycle		772,240	7,756,972					8,529,213		
A-CFS-1	Number of experimental cycle	20,000	20,000	20,000	20,000	15,830				148,256,151	18.7
	Number of equivalent cycle	20,000	772,239	13,137,391	44,075,395	105,332,371			163,317,396		
A-CFS-2	Number of experimental cycle	20,000	20,000	20,000	20,000	11,300					
	Number of equivalent cycle	20,000	772,239	13,137,391	44,075,395	75,189,879			133,194,905		
B-RC-1	Number of experimental cycle			20,000		15,135				12,814,782	-
	Number of equivalent cycle			1,296,903		9,941,720			11,238,624		
B-RC-2	Number of experimental cycle			20,000		19,934					
	Number of equivalent cycle			1,296,903		13,094,037			14,390,941		
B-CFS-1	Number of experimental cycle			20,000		20,000	20,000	13,480		263,822,131	20.6
	Number of equivalent cycle			1,296,903		13,137,391	93,053,635	150,635,099	258,123,028		
B-CFS-2	Number of experimental cycle			20,000		20,000	20,000	14,500			
	Number of equivalent cycle			1,296,903		13,137,391	93,053,635	162,033,304	269,521,233		

of B-RC-1 and 2, the unreinforced RC slab specimens. The fatigue failure patterns of all specimens in this test are shown in Fig. 5.

In case of Type A, for the destruction pattern of specimen A-RC-1, 2, cracks formed in two directions, as shown in Fig. 5(a) [1, 2] at the same positions where reinforcement bars were laid out. Peeling occurred in areas under the influence of the Dowel effect. As for the destruction of A-CFS-1, 2, peeling were caused by the Dowel effect over a wide area, as shown in Fig. 5(a) [3, 4] and shallow peelings were observed in the surrounding areas. Peeling on RC slabs with CFS bottom side adhesion reinforcement is considered to have been caused by concrete in the RC slabs. In all

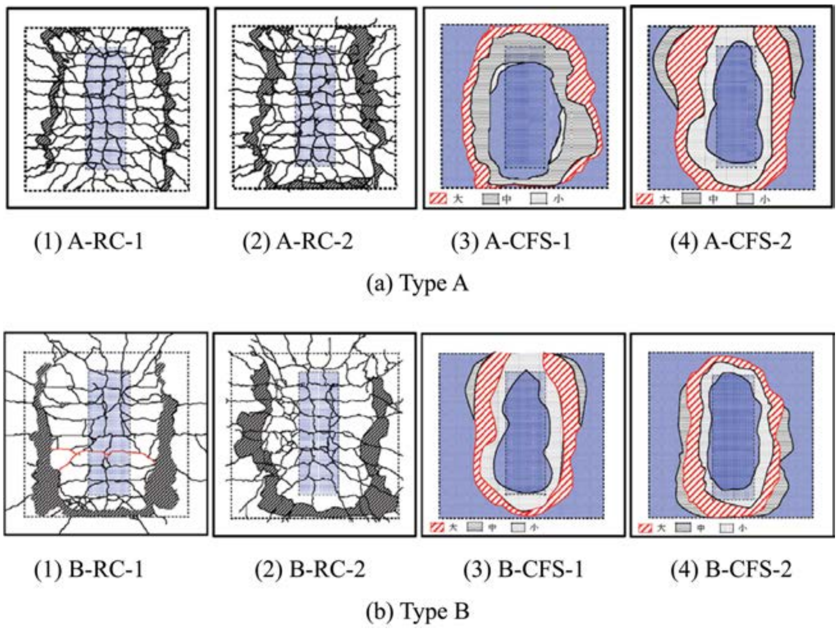


Fig. 5. Fatigue failure patterns of RC Slabs.

specimens, punching shear destruction under a running wheel load was observed, and CFS breakage was not found.

In case of Type B, for the destruction pattern of specimen B-RC-1, 2, cracks formed in two directions on the positions of reinforcement bars, as shown in Fig. 5(b)[1, 2]. This is the same as in the type A RC slabs. In addition, peeling occurred over an area affected by the Dowel effect. As for B-CFS-1, 2, peeling over a wide area under the influence of the Dowel effect were also observed, as shown in Fig. 5(b) [3, 4]. However, compared to B-RC-1, 2, the extent of cracks and peeling was lower. In the type B specimens, as with types A, punching shear destruction under a running wheel load was observed, and CFS breakage was not found.

Based on the results above, fatigue resistance is considered to have increased as crack formation was suppressed with a decrease in cracks and peeling, although the number of equivalent cycles increased.

Conclusions

(1) Research and development of a hybrid repair method is required. This method should be capable of reducing construction duration, repairing micro cracks, and preventing post-repair crack formation by integrating self-healing materials to the adhesive-backed CFS repair materials, which are easy to apply.

(2) For comparison, the number of equivalent cycles of an unreinforced RC plane was used as the reference. The CFS adhesion types A and B showed 18.7-fold and 20.6-fold increase, respectively, in the number of equivalent cycles, thus verifying the reinforcing efficacy of the CFS adhesive backing.

(3) The unreinforced RC plane specimens exhibited failure morphology including bidirectional cracks and local interfacial delamination in the range of the dowel effect. The CFS-reinforced RC plane specimens demonstrated crack inhibition owing to CFS adhesion and increase in fatigue resistance, although delamination was observed in the range of dowel effect, and the CFSs resisted specimen failure.

References

1. Chiba prefecture: long-life repair plan report, Chiba environment and road maintenance unit (2010).
2. Japan Road Association: Specifications for highway bridges · East commentary (2002).
3. Ministry of land, Infrastructure, Transport and Tourism: Trends in long-life repair plans for municipalities (2011).
4. Japan Society of Civil Engineering: Highway bridge slab maintenance manual (2012).
5. T.H. Ahn, T. Kishi, Journal of Ceramic Processing Research 16 [1] (2015) (2015) 117-123.
6. FORCA Tou sheet · Strand sheet bottom side plan construction bill of quantity, Nippon Steel & SumikinMaterials Co., LTD (2013).
7. The design and construction guidelines (plan) for the repair and reinforcement of highway bridge concrete parts using adhesive-bottom side carbon fiber sheets (CFS), Public Worls Research Institute JAPAN (1999).
8. M. Shigeyuki, Highway bridge slab design · construction and maintenance (2007).