Journal of Ceramic Processing Research. Vol. 16, Special. 1, pp. 149s~155s (2015)

JOURNAL OF
Ceramic
Processing Research

A Study on the reinforced CFS using the concept of self-healing repair methods in bottom side for damaged highway RC slabs

Chan-Ho Won[a], Tadashi Abe[b], Tae-Ho Ahn[c], Kwang-Bo Shim[c] and Byung-Wan Jo[d,]*
[a]*The Research Institute of Industrial Science, Hanyang University, 222 Wangsimni-ro, Seongdong-gu Seoul 133-791, Korea*
[b]*Dept. of Civil Engineering, College of Industrial Technology, Nihon University, Chiba, 275-8575, Japan*
[c]*International Sustainable Engineering Materials (ISEM) Center, Ceramic Materials Institute Division of Advanced Materials Sci. Eng., Hanyang University, Seoul 133-791, Korea*
[d]*Department of Civil and Environmental Engineering, Hanyang University; 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Korea*

In 2004, Japan's Ministry of Land, Infrastructure, Transport and Tourism conducted an inspection and surveyed the bridges constructed on major routes, there through most severe damages are associated with the deterioration damages caused by fatigue of the RC slabs.
Therefore, in this study, an analysis was conducted on the damaged state of aging bridges, and cases of maintenance and reinforcement in accordance with the damaged state were examined. Furthermore, the reinforcement effect and fatigue resistance of the CFS in regard to the RC slab was evaluated through a fatigue test under a running wheel load which reproduces the fatigue damage through the reciprocating motion of the wheel load. Thereafter, the adhesive reinforcement method that integrates the concept of self-healing repair methods for a smart CFS undersurface was examined.

Key words: RC slabs, Reinforcement, CFS, Deterioration, Self Healing Materials, Self-healing repain methods

Introduction

In 2004, Japan's Ministry of Land, Infrastructure, Transport and Tourism [1, 2] conducted an inspection and surveyed the bridges constructed on major routes, whereby, the results were reported through the < Long Life Repair Plan for Highway Bridges >, which was published in the Chiba Prefecture for the purpose of presenting a plan regarding the prolongation of life time for bridges, along with the downward standardization of bridge maintenance costs [3] According to the report, an evaluation indicated that the parts of the bridge prone to the most severe damages are associated with the deterioration damages caused by fatigue of the RC slabs that directly receive the load of heavy vehicles [1, 2]. Therefore, the repair and reinforcement measures for RC slabs, which are associated with the most severe damages, is an important issue for the life time prolongation of bridges and the downward standardization of bridge maintenance costs, thus, research and experiment related to this issue have been conducted in an active manner. Of which, methods of adhesive reinforcement regarding the undersurface of slabs through the use of carbon fiber sheets(hereinafter: CFS) for reinforcement and maintenance purposes, which are lightweight and have excellent workability properties, has been studied as a countermeasure for the degradation of fatigue resistance and cracks caused by fatigue in regards to RC slabs on highway bridges [3].

Meanwhile in South Korea, as infrastructure facilities constructed in accordance with the rapid economic growth enter its 30-40 post-construction years, quantitative measures that responds to the aging of said infrastructure is urgently needed. Although the market size of the facility maintenance industry in South Korea has increased more than six-fold in the last 20 years, it is still drastically insufficient compared to countries with an advanced maintenance industries such as the United States, Japan, and Europe. Along with the increased interest in the maintenance of infrastructure, research on the development of smart self-healing materials that restore and repair cracks in an autonomous manner is currently being conducted in South Korea [4].

In this study, an analysis was conducted on the damaged state of aging bridges, and cases of maintenance and reinforcement in accordance with the damaged state were examined. Furthermore, RC slab specimen was produced in which the undersurface was reinforced with CFS. Also, the reinforcement effect and fatigue resistance of the CFS in regard to the RC slab was evaluated through a fatigue test under a running wheel load which reproduces the fatigue damage through the reciprocating motion of the wheel load. Thereafter, the adhesive reinforcement method that integrates the concept of self-healing repair

*Corresponding author:
Tel : +82-2-2220-0327
Fax: +82-2-2292-0321
E-mail: joycon@hanyang.ac.kr

methods for a smart CFS undersurface was examined.

The Status of Damage to Bridges in Japan

The inspection results of the bridge inspection checklist show that damages in RC slabs that directly receive the load of vehicles are the most severe and that this type of damage presents different features according to the environment or the amount of traffic in the construction area. Fig. 1-3 shows examples of damage that varies according to the location of construction and the driving environment.

Fig. 1 shows an RC slab located in a metropolitan area where there is an increase in general vehicle traffic, as well as a large number of heavy overloaded vehicles; thus, the majority of the damage to this slab is driving fatigue. Fig. 1(a) shows the state of damage on the undersurface of a new construction site for a highway that was opened in 1971 and has been serving the public for 27 years. This section is most significantly affected by the changes in load of heavy vehicles, and thus single-directional cracks at 10 to 30 cm intervals have occurred. In addition, because cracks are found in the haunch part as well, they are regarded as through cracks. Fig. 1(b) shows the damage at the exit of the highway, which is also shown in Fig. 1(1), where grid-type cracks, occurred at intervals of 20-40 cm. Fig. 1(c) shows the RC slab of typical bridges where complex damage due to two-way cracks and glass petrifaction are observed.

The damage shown in Fig. 2 is on a major route in the vicinity of the shoreline, and the majority of damage is salinity from salt in the air. As shown in Figs. 2(a) and (b), the rebars are exposed and rust caused by leakage from the cracks is present.

Fig. 3 shows damage of an RC slab of a highway bridge built on the cold front Despite the small amount of traffic, including both heavy and private vehicles, serious damage can be observed, which was caused by freezing and thawing and the spread of chloride. Fig. 3(a) shows damage caused by repeated vehicle travel; many fine cracks and scaling can be observed on the concrete cover. Fig. 3(b) shows the undersurface of Fig. 3(a), showing glass petrifaction of the cement material caused by leakage through cracks on the surface, and a crack has occurred in two directions. In Fig. 3(c), despite the well reserved surface, it is gravel from the concrete cover below compressive strength

(a) 1Direction Cracks (b) 2 Direction cracks (c) 2Direction cracks and Free lime

Fig. 1. Many large vehicle traffic areas.

(a)Rebar leakage (b) Deposition of rust (c) Rebar leakage and Rust

Fig. 2. Important route of coastal areas.

(a) scaling (b) Cracks and Free lime (c) gravel of internal

Fig. 3. Cold and snowy region.

due to a combination of factors such as frost damage from repeated freezing and thawing and chloride spread. The example slab is from a bridge demolished after 30 years of public use. The common factor in the RC slab damage mentioned above is that the cracks are made in one or two directions and composite damage was caused by the intrusion of seepage water through the cracks. Thus, the root cause of composite damage is cracks, and the use of the concept of self-healing repair method in reinforcement methods seems to be an appropriate early countermeasure in terms of prevention and maintenance. Thus, adding the concept of self-healing repair methods as a countermeasure for cracks is necessary not only for new concrete but also during maintenance and reinforcement, and further research on integrative maintenance and reinforcement for composite damage using self-healing material is required.

Countermeasures of Maintenances and Reinforcements in Japan

Currently, most commonly used RC slab reinforcement measures can largely be divided into upper surface reinforcement and undersurface reinforcement. The major construction methods of these reinforcement measures can be seen in Fig. 4 [5].

The method shown in Fig. 4(a) is the upper surface pressure method using Steel Fiber Reinforced Concrete (SFRC) for reinforcement, which is used to increase the load-carrying capacity and fatigue resistance in cases where the RC slab surface is seriously damaged. In recent years, in order to improve adhesion, methods such as the application of epoxy resin or combustion using water shot-blasting have been added to the SFRC upper surface pressure method. The method shown in Fig. 4(b) is an undersurface adhesive method using CFS, with high constructability, which is mainly used to slow down deflation, reduce stress intensity, restrain crack formation, and improve fatigue lifespan. Fig. 4(c) shows an undersurface pressure method using mortar spray. In this method as well, recent studies have investigated methods to improve adhesion by the application of epoxy resin, combustion using water shot-blasting, or using steel made of carbon fiber.

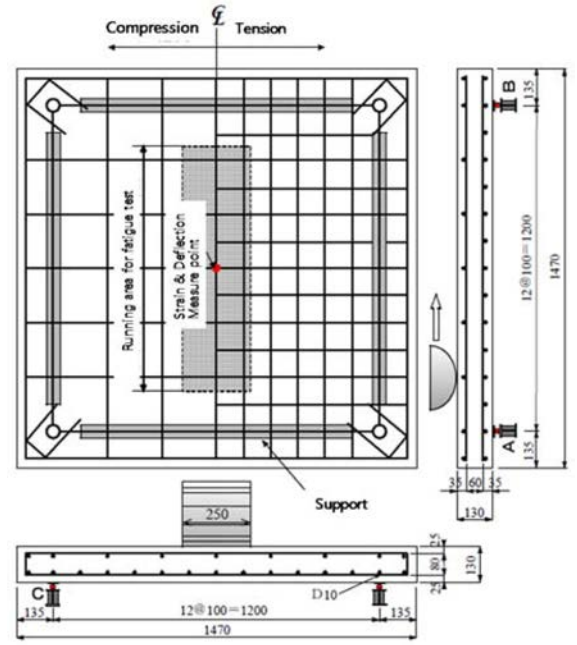


Fig. 5. Specimen size and rebar arrangement.

Experimental Procedures

Fabrication of specimens

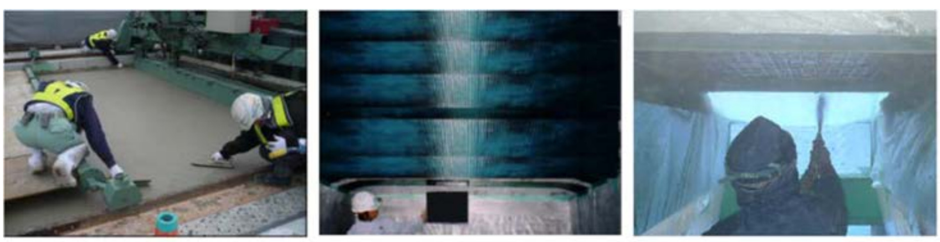
The specimen used in this study was a model built based on the provisions in the Japanese specifications for highway bridges [6], with a ratio of wheel load width (500 mm) as specified in the specifications for highway bridges. The width of the vehicle used in this study had a width of 250 mm; therefore, the specimen is a half-model. The half-model specimen is referred to as an A-type specimen. Detailed measurements are indicated in Fig. 5.

Materials

(1) *RC slab*

Portland cement was used for the A-type RC slab specimen, with less than 5 mm of crushed sand and 5-20 mm of crushed stone (JIS A 5005). The concrete mixture is indicated in Table 1. In addition, SD 295 A and D10 were used as rebar for the specimen.

The properties of the rebar and the compressive



(a) SFRC overlay (b) CFS bottom side Reinforcement (c) spraying method of mortar

Fig. 4. The main reinforcement measures.

Table 1. Mix proportions of concrete for RC slab.

Slump (cm)	W/C (%)	s/a	Unit weight (kg/m³)					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)		
			Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young's modulus (kN/mm^2)
Type A	RC	35	368	516	200
	CFS	32			

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	202	0.111	4,420	235

strength of the concrete used in the experiment are indicated in Table 2. Here, the non-reinforced RC slab is written as A-RC.

(2) *Carbon Fiber Sheet* (*CFS*)

CFS used in this experiment is a continuous fiber sheet with a unit weight of 200 g/m^2 and a designed thickness of 0.111 mm. In order to increase the adhesive strength of the RC slab and CFS, a primer and CFS adhesive was used. The properties of the CFS materials are listed in Table 3. Here, the CFS undersurface adhesive-strengthened RC slab is denoted as A-CFS.

CFS undersurface adhesive-strengthening method

In the CFS undersurface adhesive-strengthening method, first, impurities were removed from the undersurface of the RC slab, and the surface was treated for surface modification (Fig. 6, (a)).

After the surface was treated, primer was applied and impregnated in order to increase the adhesion of the concrete and CFS; the primer was cured 12 or more times (Fig. 6, (b)). Next, the entire surface of the CFS with a width of 500 mm was adhered parallel to the main rebar using epoxy-based impregnated resin for CFS and cured for more than 12 h (Fig. 6, (c)). Using the same method, the second layer was adhered perpendicular to the main rebar (Fig. 6, (d)).

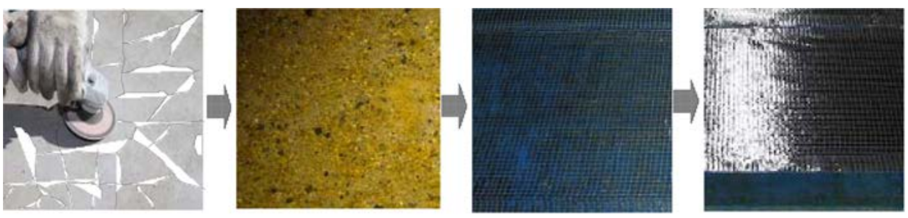
Results and Discussion

The A-type specimen built for this experiment was a half-scale model. Therefore, the reference load of the specimen was set as 60 kN, which is one-half of the 100 kN specified for highway bridges considering a safety factor of 1.2. Fatigue tests were run continuously at a range of ± 450 mm from the center of the specimen in the travelling direction. The initial loads were 80 kN and 100 kN and tests were performed 20,000 times at the initial loads. Afterwards, the load of 100 kN was increased by 10 kN after 20,000 runs. The effectiveness of the reinforcement was evaluated based on the number of equivalent cycles of a non-reinforced RC slab.

The load was increased after every 20,000 runs in fatigue tests under a running wheel load. Therefore, the number of equivalent cycles (N_{eq}) was calculated from the relation between the reference load, the load, and the number of experimental runs in order to evaluate the effectiveness of the reinforcement and fatigue resistance. Assuming that the number of equivalent cycles according to wheel load run is on the minor side, it can be expressed by Equation (1). Furthermore, for m, the inverse number of the slope of the S–N curve used in Equation (1), a value of 12.7, proposed by Matsui, was applied [7].

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

Here, Pi is the load (kN), P is the reference load



(a) Surface treatment (b) Primer (c) 1st layer (d)2nd layer

Fig. 6. Adhesion processing of CFS.

Table 4. Damage classification and damage condition of the rc slab indicated in the inspection checklist.

Damage Category	The Degree of Observable Cracks	Damage C ondition	Cumulative damage $D = N/N_f$	General conditions regarding debonding and Rebar Exposure		General conditions regarding leakage and glass petrifaction	
a	Cracks are mainly in a single direction, the minimum distance between cracks are generally more than 1 m The width of the crack is less than 0.5 mm		D < 0.10	No damages		No damages	
b	1.0 to 0.5 m, the cracks are mainly in a single direction, and although cracks occur in a perpendicular direction to the main crack, they do not form a grid pattern Although the majority are under 0.1 mm in width, cracks over 0.1 mm exist		0.10 D < 0.20				
c	Immediately before forming a grid pattern of approximately 0.5 m Although the majority are under 0.2 mm in width, cracks over 0.2 mm exist		0.20 D < 0.50	Occurrence of only debonding		Leakage occurs from the crack, but rust and glass petrifaction is barely visible	
d	The formation of 0.5 to 0.2 m grid patterns Cracks over 0.2 mm are noticeable, and partial debonding is visible		0.50 D < 0.75	Although rebar is exposed, corrosion of rebar minor		Leakage occurs from the crack, but rust is barely visible	
e	The formation of grid patterns that are under 0.2 m in size Cracks over 0.2 mm are more noticeable, along with the occurrence of continuous debonding		0.75 D < 0.80	Rebar is exposed, and noticeable corrosion has occurred		A noticeable amount of leakage and glass petrifaction occurs from the crack, a mixture of rust is confirmed from the leakage	
–			0.80 D < 1.0				

(60 kN), n_i is the number of experimental runs, and m is the inverse number of the slope of the S-N curve (12.7)

The categorization of fatigue damage regarding RC slabs on highway bridges

The purpose of evaluating the fatigue resistance of an adhesive strengthening method for an undersurface using CFS is to identify the optimum reinforcement cycle through maintenance plans and reinforcement methods in regards to RC slabs on highway bridges that are significant damaged. For this reason, the relationship between damage categorization and the deterioration process indicated in the [Standard Specifications for Concrete (For Maintenance)] [8]by the Society of Civil Engineers, as well as the inspection details for highway bridges indicated in the inspection checklist are shown in Table 4.

(1) *Number of Cycles to Failure*

When estimating fatigue deterioration regarding RC slabs, the number of cycles to failure, N_f, is calculated from the equation for the S–N curve of RC slabs. Thus, N_f can be expressed as shown in Equation (2).

$$N_f = 10^{\beta} \tag{2}$$

$$\beta = [\log(S)-\log(P/P_{sx})]/\mathrm{m} \tag{2.1}$$

Where, S is the S value on the S-N curve, m is the reciprocal of the absolute value of the S-N curve, P is the reference load (kN), and P_{sx} is the punching shear force (kN).

The years of usage that lead to the failure of the RC slab can be expressed as shown in Equation (3).

Years of usage = the equivalent number of cycles to failure / (the capacity of planned traffic in a single direction for 1 day × 365 days) (3)

(2) *The Degree of Cumulative Damage*

In regards to the relation between the degree of cumulative damage D and the deterioration process, Tamakoshi [9] established the ratio of N_f and the cumulative number of cycles, N, as the degree of cumulative damage, D, which can be expressed as shown in Equation (4) through the minor linear damage accumulation method.

$$D = N/N_f \tag{4}$$

Where, N is the number of cycles.

Although current inspection checklists estimate the remaining lifetime by examining mainly the damage caused by cracks, factors such as deboning and exposure of rebar, as well as leakage and glass petrifaction caused by the bridge deck waterproofing method depending on the installation occur in actual RC slabs on bridges. Therefore, an evaluation method that incorporates the degree of cumulative damage D and the checking processes considering the complex deterioration factors is required.

(3) *Damage condition of the RC slab's damage classification based on inspection checklist*

Checks the statuses of a real bridge were damaged in the Fig. 1, Fig. 2, and Fig.3. Fig. 1 shows an RC slab located in a metropolitan area where there is an increase in general vehicle traffic, as well as a large number of heavy overloaded vehicles; thus, the majority of the damage to this slab was driving fatigue. Fig. 1 (a)'s damage classification, as shown in Table 4, is c, corresponding to progression of the degradation process as proposed by the Society of Civil Engineers. And shown in Fig. 1 (b)'s damage classification and deterioration process are presented in Fig. 1(a). And shown in Fig. 1 (c)'s damage classification is d, corresponding to the acceleration stage the former period of the deterioration process.

The damage shown in Fig. 2 is on a major route in the vicinity of the shoreline, and the majority of damage is salinity from salt in the air. Thus, rebars are exposed and rust caused by leakage from the cracks is present. Therefore, the damage can be classified as d, and the deterioration process seems to be at the acceleration stage (the late period)

Fig. 3 shows damage of an RC slab of a highway bridge built on the cold front. But, serious damage can be observed, which was caused by freezing and thawing and the spread of chloride despite the small amount of traffic. Fig. 3 (a) and Fig. 3 (b)'s damage can be classified as e, and the deterioration process seems to be at the deterioration stage, where reinforcement is not possible.

Table 5. Number of equivalent cycles.

Test Specimen	Total number of Equivalent cycle	Average number of equivalent cycle	Number of equivalent cycle ratio
A-RC-1	7,346,848	7,938,030	-
A-RC-2	8,529,213		
A-CFS-1	163,317,396	148,256,151	18.7
A-CFS-2	133,194,905		

Fatigue test under running wheel load

The number of equivalent cycles for the A-type specimen's non-reinforced RC slab and the CFS undersurface adhesive-strengthened RC slab is given in Table 5.

The number of equivalent cycles N_{eq} for A-RC-1, the A-type non-reinforced RC slab specimen, is 7.3 × 106 cycles, the number of equivalent cycles N_{eq} for specimen A-RC-2 is 8.5 × 106 cycles, and the average number of equivalent cycles N_{eq} for A-RC-1,2 is 7.9 × 106 cycles. Furthermore, the number of equivalent cycles N_{eq} for specimen A-CFS-1CFS, the undersurface adhesive-strengthened RC slab, is 163.3 × 106 cycles, the number of equivalent cycles N_{eq} for A-CFS-2 is 133.1 × 106 cycles, and the average number of equivalent cycles N_{eq} for A-CFS-1,2 was 148.2 × 106 cycles. The number of equivalent cycles N_{eq} for A-CFS, the CFS undersurface adhesive-strengthened RC slab, was approximately 18.7 times higher than the number of equivalent cycles N_{eq} for A-RC, the non-reinforced RC slab.

Conclusions

(1) A life-expectancy prediction evaluation method that combines a fatigue test under a running wheel load with inspections considering complex deterioration should be contemplated.

(2) The common factor in cases where the RC slab was damaged was that cracks were made in one or two directions, and composite damage was caused by the intrusion of seepage water through the cracks. For this reason, adding the concept of self-healing repair methods as a countermeasure for cracks is necessary not only for new concrete but also during maintenance and reinforcement. Thus, further research on integrative maintenance and reinforcement for composite damage using the concept of self-healing repair methods should be conducted.

(3) A fatigue test under a running wheel load was conducted after strengthening the adhesion of the undersurface of an RC slab using carbon fiber sheets, and the results indicated that the number of equivalent cycles increased 18.7 times as compared to the non-reinforced RC slab.

References

1. Ministry of land, Infrastructure, Transport and Tourism : Periodic bridge inspection (list), 2004.
2. Ministry of land, Infrastructure, Transport and Tourism: Trends in long-life repair plans for municipalities, 2011.
3. Chiba prefecture:long-life repair plan report, Chiba environment and road maintenance unit, 2010.
4. T.H. Ahn, T.Kishi "Effect of self-healing agents on inorganic crack repair materials for concrete infrastructures", Journal of Ceramic Processing Research, Vol. 16, No.1, pp.117-123 (2015).
5. Japan Society of Civil Engineering : Highway bridge slab maintenance manual, 2012.
6. Japan Road Association : Specifications for highway bridges · East commentary, 2002.
7. Matsui Shigeyuki:Highway bridge slab design · construction and maintenance, 2007.
8. Japan Society of Civil Engineering:Concrete standard specifications [Maintenance], 2008.
9. Takashi TAMAKOSHI, Masanori OKUBO, Youta WATANABE : Research on highway bridges management [Bridge Management System], TECHNICAL NOTE of National Institute for Land and Infrastructure Management, No.523, 2009.