

RESEARCH ON STEEL FIBER REINFORCED CONCRETE PAVEMENT FOR ORTHOTROPIC STEEL DECK AS A COUNTERMEASURE FOR FATIGUE

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Abstract

This paper describes ongoing studies about application of Steel Fiber Reinforced Concrete (SFRC) pavement for existing orthotropic steel deck as a countermeasure for fatigue problems. Public Works Research Institute (PWRI) and several companies are now conducting joint researches on repair/reinforcement methods including SFRC pavement. In order to evaluate durability of the pavement, strength tests and fatigue tests under negative bending have been conducted using half meter size specimens taking into account of effects of reinforcement in SFRC and influence of water. Wheel running test using real size specimen will get started in the beginning of 2008.

Introduction

Orthotropic steel deck (OSD) is widely applied to long span bridges and urban viaducts in Japan because its light weight contributes to reduce their dead load. In the early decades of application of OSDs, valve plates were used for longitudinal ribs, then trough ribs had been increasing through 1970's, and it became common in 1980's. Trough ribs have some advantages that they can be fabricated by one side welding and bring more longitudinal rigidity so that spacing of transverse ribs can be widened. During 1990's, fatigue cracks observed in OSDs had been a few types, however many types of cracks are observed in recent years as depicted in Figure 1. They are¹⁾;

1. Fillet weld between deck plate and trough rib
 - 1-1. Crack propagates into deck Plate
 - 1-2. Crack propagates into bead
2. Fillet weld between transverse rib and trough rib
3. Butt weld connection of trough rib
4. Fillet weld between vertical stiffener and deck plate

If Crack 1-1 penetrates a deck plate, it threatens not only to cause damage on pavement but also to deteriorate serviceability and safety to the traffic. What is worse is that Crack1-1 is invisible until it causes visible damage on the pavement. Therefore PWRI has given priority to investigate this type of fatigue crack. Crack1-2 is also problematic because the number of this type of crack is increasing, it is fast growing, and it tends to

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propagate into deck plate and/or trough rib webs eventually. The cause of these types of crack is guessed that local bending of deck plate induces high stress concentration at root of trough rib weld as shown in right bottom of Figure 1. Since the damaged cases are increasing, research on the cause of cracks and developments of repair/reinforcement methods are strongly needed. It is the same for crack 3 and 4.

PWRI and some private companies had begun six joint researches in 2005 as shown in Figure 2. Researches and targeting methods are categorized in two, the one is reinforcement mainly by steel members as (a) ~ (c) in Figure 3, and the other is improvement of pavement as (d) in Figure 3. For the latter, SFRC pavement is expected to be one of appropriate methods because it reduces local bending of the deck plate at the weld root of trough rib without major increase of dead load. Several OSD bridges in Japan have already applied SFRC pavement. For crack 3 and 4, we have conducted studies by FEM²⁾³⁾, and are now doing wheel running test for crack 4.

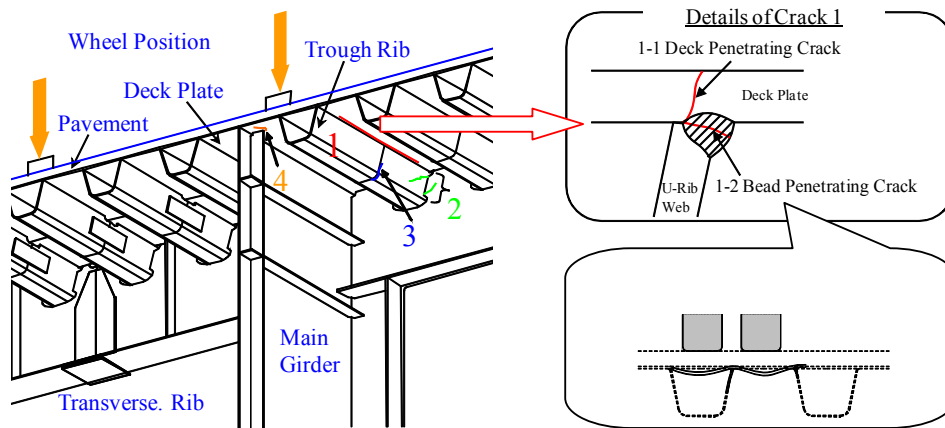


Figure 1 Fatigue Cracks in Orthotropic Steel Deck

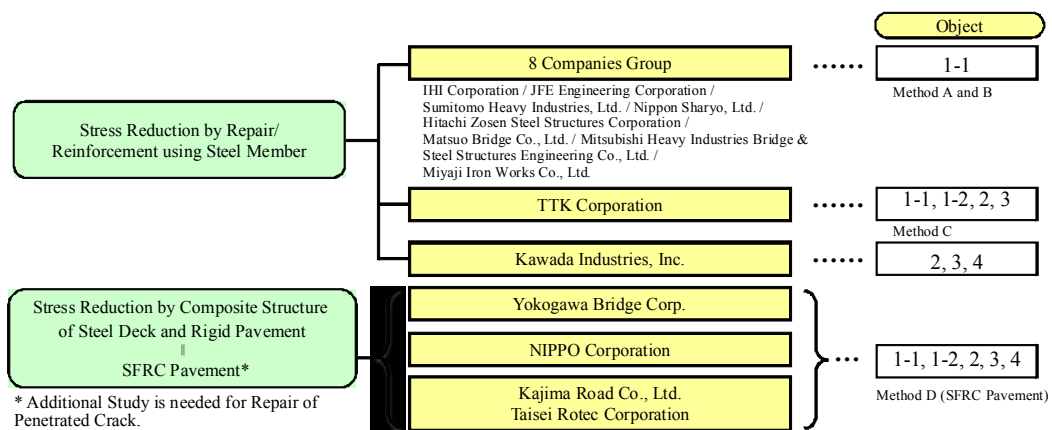


Figure 2 Joint tasks between PWRI and Companies

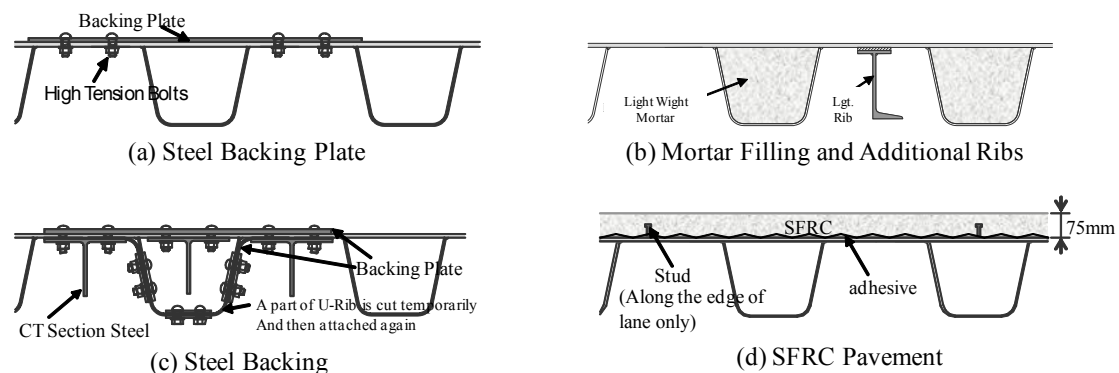


Figure 3 Repair/Reinforce Methods under investigation in PWRI's Joint Research

Literature Review

Using concrete pavement on OSD as a countermeasure for fatigue has been tried not only in Japan. Moergijk bridge in Netherlands was resurfaced using 50mm thickness of high performance reinforced concrete⁴⁾. In Japan, Nagoya Expressway Public Corporation (NEPC) had used SFRC pavement in 1980's for several ramp bridges, though, the application was not for fatigue but for stabilizing pavement on ramp bridges with slope⁵⁾. And another difference is that NEPC's SFRC is connected to deck plate only by studs as shown in Figure 4. As a countermeasure for fatigue, Japan's first application was on Yokohama Bay Bridge (YBB)'s lower deck in 2004. The upper deck had already been opened to traffic since 1989. Since the lower deck was additionally constructed, the SFRC pavement was not repair/ reinforcement of existing structure. Early strength cement was used for SFRC whose thickness was 75 mm⁶⁾. Adhesive was used all over the deck plate to connect SFRC. Studs were set, avoiding wheel load paths, only at the center of the lane and the edges of SFRC in transverse direction. And in longitudinal direction, they are put in two lines manner with 300mm spacing each other. After the completion of the SFRC pavement, cracks on SFRC were found as shown in Photo 1. Major cracks are longitudinal and its maximum width is 0.3mm⁷⁾. The cracks had been filled with acrylic. Thanks to the upper deck, rainfall does not seem to affect so much and in fact, no deterioration has been observed in terms of performance as pavement yet. However, this incident has brought a major concern about durability of SFRC Pavement.

As a repair/reinforcement of fatigue damaged OSD bridges in service, Shonan Ohashi Bridge was the first application of SFRC pavement. The bridge had had many fatigue cracks in its trough rib weld (1-1 and 1-2 in Figure 1) so that a thorough measure had been needed. The replacement of existing asphalt with SFRC and 250-500mm shift of traffic lanes were carried out in 2005. In order to complete the replacement under the condition that the bridge was to be opened to traffic daytime and closed only from 9 p.m. to 6 a.m., two night process was repeated little by little. In the first night, existing pavement was eliminated and the deck plate was temporarily paved. In the second night, the

temporary pavement was peeled off, and then SFRC was paved and cured. Ultra-rapid hardening cement was used for SFRC to get enough strength to open to traffic in the morning. Adhesive was mainly used to connect SFRC to deck plate as in the case of YBB. Studs were set only along both edges of the pavement in two lines manner. The difference from YBB is that grid of Carbon Fiber Reinforced Plastic (CFRP) was set in the middle of 70 mm thickness of SFRC. CFRP is expected to restrain crack widths and to keep rigidity of composite of SFRC and deck plate⁸⁾. In recent applications, Metropolitan Expressway Co. Ltd. has replaced a part of pavement to SFRC on OSD bridges that was damaged by fatigue. 50mm thickness of SFRC is used as lower layer and 30mm thickness of upper layer is paved on waterproof layer on the SFRC⁹⁾. The upper layer uses porous asphalt mixture. More applications are expected in Japan, for both existing and newly constructed OSD bridges.

Researches on SFRC so far have been usually conducted through experimental ways, such as construction experiments and fatigue tests by several entities. Japan Construction Method and Machinery Research Institute (CMI) had conducted wheel running test using real size specimens twice for the joint research between Metropolitan Expressway Co. Ltd. and Nippon Expressway Research Institute Co. Ltd. The latest tests took into account of effect of water¹⁰⁾¹¹⁾. One of members of PWRI's joint research, Yokogawa Bridge Co. (YBC) had conducted Static loading test¹²⁾ and wheel running tests¹³⁾ for both type of SFRC Pavement shown in Figure 4. And Hiratsuka Doboku Office of Kanagawa Prefecture had conducted a fixed point cyclic loading test to determine the pavement structure of their Shonan Ohashi Bridge using PWRI's testing machine¹⁴⁾.



Photo 1 Acrylic-Injected SFRC Pavement on Yokohama Bay Bridge

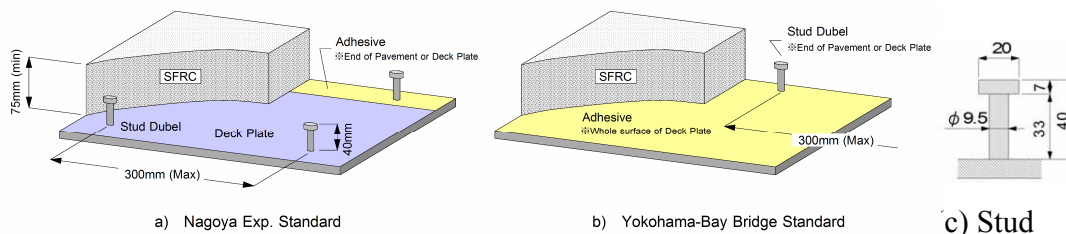


Figure 4 Types of SFRC pavement

Overview of the research

In this paragraph, PWRI's research is mentioned. In order to establish the SFRC pavement as an anti-fatigue technology, followings are needed to be evaluated. One is to confirm the improvements of fatigue performance of OSD, the second is to evaluate SFRC's durability, and third is to clarify whether any side-effects occur or not, for example, since it is more rigid than asphalt, a bridge's behavior may change after SFRC pavement. In addition, though PWRI is not dealing with all, followings are related to SFRC pavement on OSD; material properties of SFRC and adhesive, construction management, maintenance method, re-paving procedure in the future, travelling performance, etc.

For the improvements of fatigue performance, stress reductions were observed in the test by YBC as a part of our joint research. Some of results derived from FE Analysis also indicate stress reduction. To evaluate durability of SFRC is the largest task in current researches especially in the case that SFRC has got cracks by negative bending under wet condition. PWRI had conducted a flexural strength test and a fatigue test using specimens having half meter by half meter size. The tests took into account of the effects of reinforcement in SFRC layer such as grids of reinforcing bar and CFRP. And in 2008, we will start a series of wheel running tests using two real size OSD specimens in order to evaluate durability of SFRC pavement under more realistic way that can re-create complicated behavior. Through these analytical and experimental studies, we plan to write a design and construction manual, hoping it becomes a useful reference for road administrative organizations that are going to apply SFRC pavement to their OSDs.

Finite Element Analysis

Analytical studies have been conducted using 3-D finite element model in order to confirm the effect on fatigue performance and to investigate the behavior in terms of durability. The model of OSD shown in Figure 5 consists of solid elements for modeling details of geometry of trough rib weld. Principle stresses are calculated at the root of trough rib weld in three models; "without pavement", "with asphalt", and "SFRC pavement". Since it is difficult to determine the rigidity of asphalt, two values are used for Young's modulus that are 1,500 and 4,000 N/mm² to correspond 20 and 7 Celsius at surface of the asphalt, respectively. According to the result in Table 1, the minimum principle stress at weld root is 65N/mm² for the model with SFRC and 201N/mm² for the model with asphalt having 1,500N/mm² Young's Modulus. If the slope of Stress-Number curve is assumed to be 3 for the weld, stress reduction into one third means twenty seven times fatigue life.

For the evaluation of durability of SFRC, it is important to know the behavior of SFRC when subjected to negative bending at the location of main girder (stringer). Tensile strain is calculated in a model without crack and crack width is calculated in a model with crack. To get maximum tensile strain, wheel load positions are examined iteratively.

Figure 6 shows strain at the surface of SFRC when the right and left wheels of two axes are striding on both sides of the main girder. Each wheel load is 50kN so that one axis with four tires is 200kN. The maximum tensile strain is 192 micro at the main girder location. According to 15), SFRC is expected to get cracked when its tensile strain becomes 200 to 300 micro approximately. There is a record that 300kN was measured as the maximum axial load¹⁶⁾. And taking account of dry shrinkage's effect on tensile strain, it seems to be likely that SFRC gets cracked under the condition in service.

In the case that SFRC has got cracked, crack width by negative bending is thought to affect the durability of SFRC and adhesive if water comes into the cracks. In order to know realistic value of crack width and to reflect it to the test, a FE model using double nodes for the crack surface is calculated. Wheel load positions are the same as in Figure 6. As shown in Figure 6, crack width is 0.1mm at the surface of SFRC.

Table 1 Stress at the root of trough rib weld

Pavement	Young's modulus (N/mm ²)	Poisson's Ratio	Maximum principle stress (MPa)	Minimum principle stress (MPa)	Note
Without Pavement	---	---	53.8 (3.20)	-614 (3.05)	
Asphalt	1,500	0.4	16.8 (1.00)	-201 (1.00)	20 Celsius degrees at surface of pavement
	4,000	0.4	8.70 (0.52)	-125 (0.62)	7 Celsius degrees at surface of pavement
SFRC	30,000	0.167	1.57 (0.09)	-65 (0.32)	

* Values in parentheses denote ratios to the value of Asphalt pavement having 1,500 N/mm² of Young's modulus.

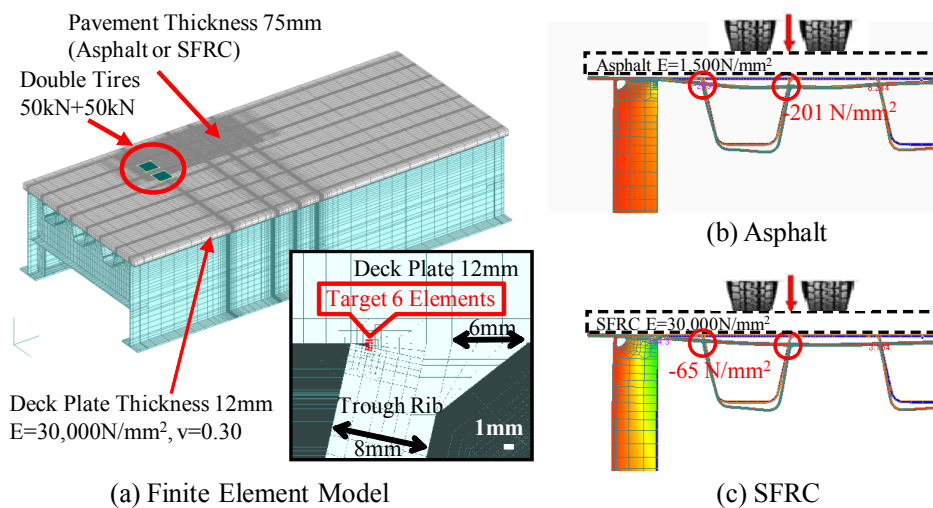


Figure 5 Finite Element Model and Results

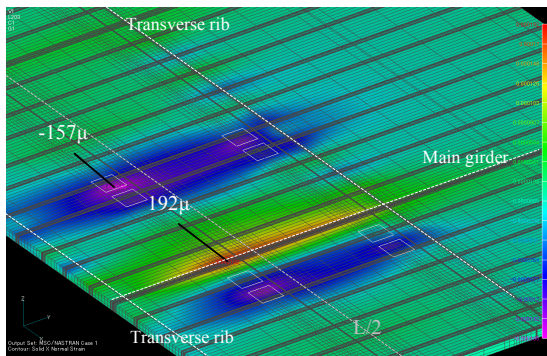


Figure 6 Tensile Strain of SFRC

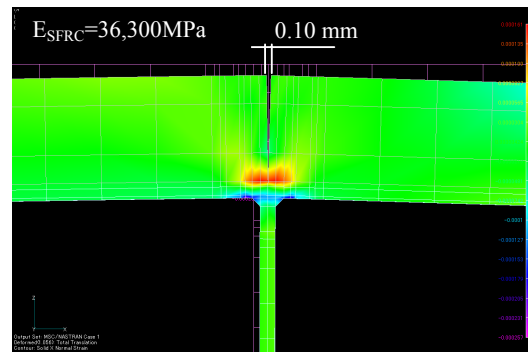


Figure 7 Crack Width

Flexure Strength Test under Negative Bending

Flexure strength tests in negative bending were conducted to investigate crack behaviors and failure modes of SFRC pavement on steel deck plate. Specimen used are shown in Figure 9, which consists of 500mm*400mm*75mm SFRC and 12mm thickness deck plate. The two are connected by epoxy adhesive only. As shown in Table 2, "Plain" does not have any reinforcements, "Re-bar" has reinforcing bar, and "CFRP" has Carbon Fiber Reinforced Plastic inside SFRC. Three specimens are tested for each type. SFRC uses ultra-rapid hardening cement and 100 kg/m³ of steel fiber. Fiber has 0.6mm diameter and 30mm length. Load arrangement for negative bending is shown in Figure 10.

Loads and tensile strain when crack initiates at the top surface are shown in Table 3. Crack loads are defined as the last value of measured load in testing machine before pi gauges have got rapid increases. And crack strain is defined as the average value derived from two pi gauges at the surface of SFRC when crack load acts. Measured crack loads are 50kN in average sense and crack strain ranges from 177 to 445 micro. In these values, major difference is not clear between three types. According to FE analysis, test load of 36.6kN corresponds to axial load of 200kN on a bridge. And 16) says crack strain of SFRC is 260 to 280 micro for 7days age. Since the measured axial load is 300kN, it is likely that crack initiates in real situation. Relation between loads and crack widths for the second specimen of each type are depicted in Figure 11. They are almost the same in the linear behaviors before crack initiations, crack loads, and rapid growth to 0.2 mm of crack width right after the crack initiation. Changes of neutral axes locations are depicted in Figure 12, which are interpolated from strains measured at the side surfaces of the second specimen of each type. In the figure, solid line indicates the border between SFRC and steel plate, and dotted lines indicate neutral axes locations when SFRC and steel plate are composite or neutral axes of steel plate. It shows that neutral axes locations move rapidly into steel plate right after the crack initiations in all three specimens. Figure 13 shows distribution of crack widths measured by strain gauges at the side surfaces of SFRC. The values were derived from the only one crack that initiated on the side surface. Dashed and dotted lines

indicate location of CFRP and Reinforcing bar, respectively, which are measured after the tests, though their designed locations are in the middle of SFRC thickness. The inclined lines that are derived from averages in each type indicate small differences between reinforcement types. Crack widths become smaller in order of Plain, CFRP, and Re-bar, probably depending on rigidities. In Photo 2, just one crack can be seen at the middle of the specimen in each photo. It is not clear whether reinforcement disperses crack initiations or not.

Table 2 Specimens for Flexure Strength Test

Specimen	Plain	Re-bar	CFRP
Cement	Ultra rapid hardening cement		
Steel Fiber	$\phi 0.6\text{mm} \times 30\text{mm}$ 100kg/m^3 (1.27 vol.%)		
Adhesive	Epoxy adhesive (1.4kg/m^2)		
Reinforcement	---	Reinforcing bar 100×100 grid $A=31.67\text{mm}^2$	CFRP 100×100 grid $A=39.2\text{mm}^2$
Number of Specimens	3	3	3

Table 3 Loads and Strain when Cracks Initiate

Specimen (reinforcement)	Crack Load (kN)	Crack Strain (μ)
Plain	1	49.3
	2	50.3
	3	47.0
Re-bar	1	51.7
	2	47.0
	3	51.3
CFRP	1	56.1
	2	51.7
	3	51.8

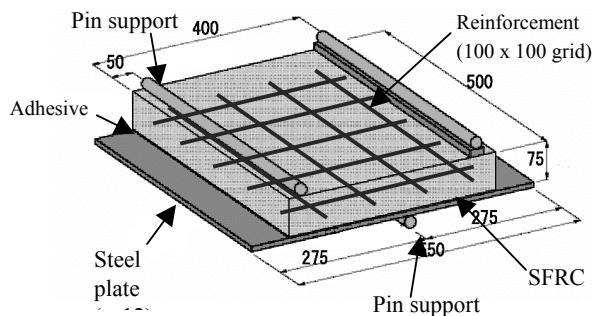


Figure 9 Specimen for Negative Bending Test

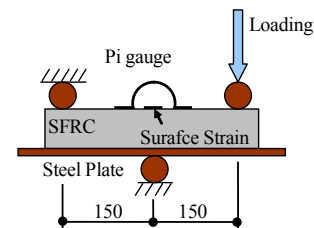


Figure 10 Loading Arrangement

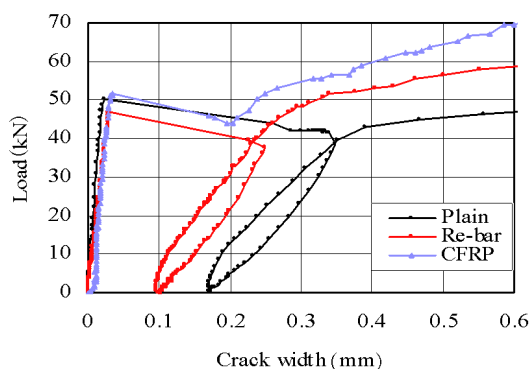


Figure 11 Loads - Crack width Curve

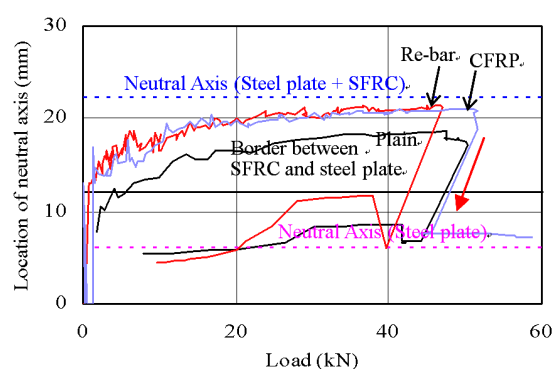


Figure 12 Changes of Neutral Axis Locations

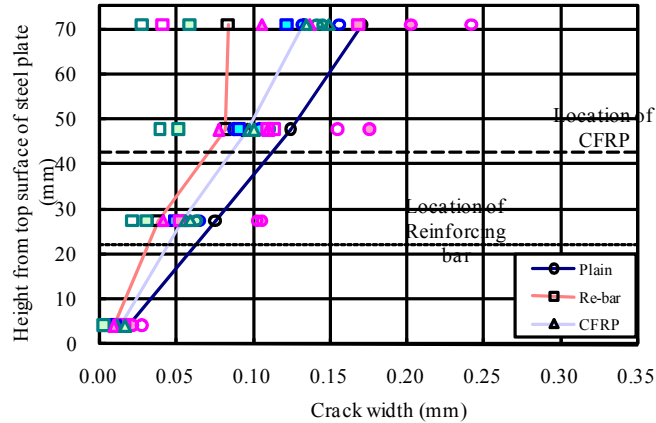


Figure 13 Crack width distributions at side surface of SFRC

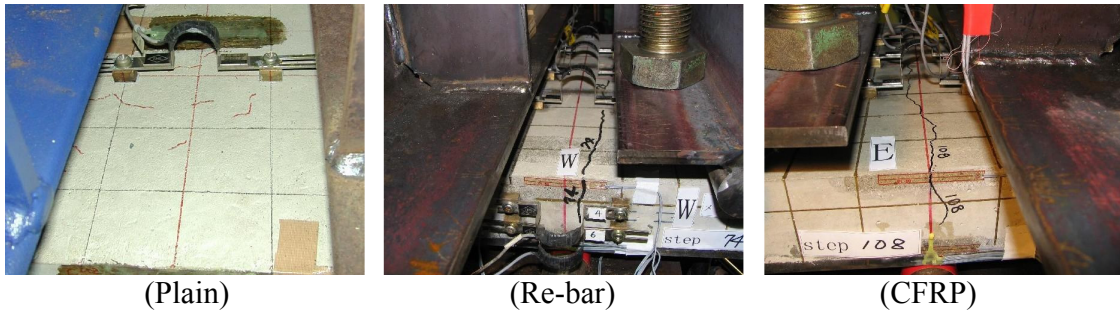


Photo 2 SFRC right after the Crack initiations

Fatigue Test

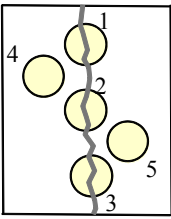
In order to evaluate effects of reinforcement and water under cyclic negative bending, fatigue tests were conducted using specimens having the same dimensions and reinforcements as the flexure strength tests. Before the cyclic loading, cracks were introduced in SFRC by static loading. Since crack width by 200kN axial load is calculated 0.1mm in FEM (Figure7), the test is controlled so as to make crack width range 0.2mm taking account of 300 kN of the measured maximum axial load. So the cyclic loading is not 'load controlled' but 'displacement controlled', in which testing machine is controlled to make crack width range 0.2mm and to make the minimum load 2kN. During the first 100,000 cycles, test was under dry condition. After the first stage, water was poured into "pool" on the top surface of SFRC and displacement and minimum load of testing machine were adjusted again. The cyclic loading was resumed and continued until 2,000,000 cycles. Three specimens were tested for each "Plain", "Re-bar", and "CFRP" type.

Changes of testing machine load and maximum crack widths are shown in Figure 13. Machine load for "Plain" decreases in the early stage and seems no changes after

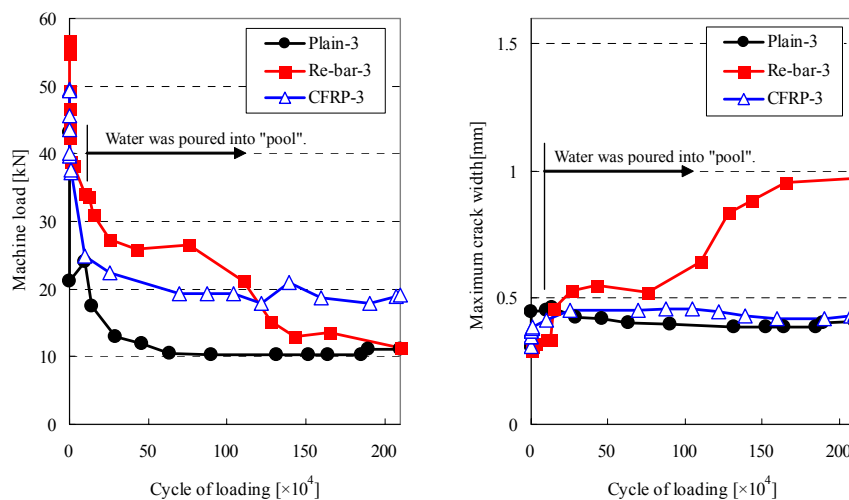
500,000 cycles. It looked that only deck plate was resisting against loads. Maximum crack widths had been 0.4mm through the test. “Re-bar” indicates higher rigidity at the early stage than “Plain” but machine load decreased to the same value as “Plain” at the end of 2,000,000 cycles. It is thought that interface between reinforcing bar and concrete had failure little by little after water pouring. The crack width became 1.0 mm. Since “Re-bar” has relatively high rigidity, it is likely that larger load was imposed to cause the targeted crack width range. And in “CFRP”, reduction of machine load seems to stop after 600,000 cycles. Load range at the end of the test is 20kN, which is twice as “Plain”. It seems that CFRP helped the deck plate resist against load. Propagation of cracks is visualized in Photo 3 by infiltration of Uranine pigment powder. It seems that crack tips do not reach the deck plates in “Plain” and “CFRP”, on the other, crack tip of the “Re-bar” not only reaches deck plate but it also tears up SFRC from deck plate 50 mm approximately. Table 4 shows results of tensile test after the fatigue tests. Adhesive strength decreases at the location of crack (1, 2, and 3) in “Re-bar” but not in “Plain” and “CFRP”. And even in “Re-bar”, strength does not decrease at several centimeters distant from crack (4 and 5).

Table 4 Results of Tensile Test

Location of Test	Plain		Re-bar		CFRP	
	Tensile Strength (N/mm ²)	Location of Failure	Tensile Strength (N/mm ²)	Location of Failure	Tensile Strength (N/mm ²)	Location of Failure
1	1.40	SFRC	0.69	Interface*	1.02	SFRC
2	1.40	SFRC	0.32	Interface*	1.15	SFRC
3	2.04	SFRC	0.25	Interface*	1.02	SFRC
4	1.53	SFRC	1.02	SFRC	1.02	SFRC
5	1.40	SFRC	1.02	SFRC	1.15	SFRC



* Interface between steel plate and adhesive.



(a) Changes of Machine load (b) Changes of Maximum Crack Width
Figure 14 Results of Fatigue Test

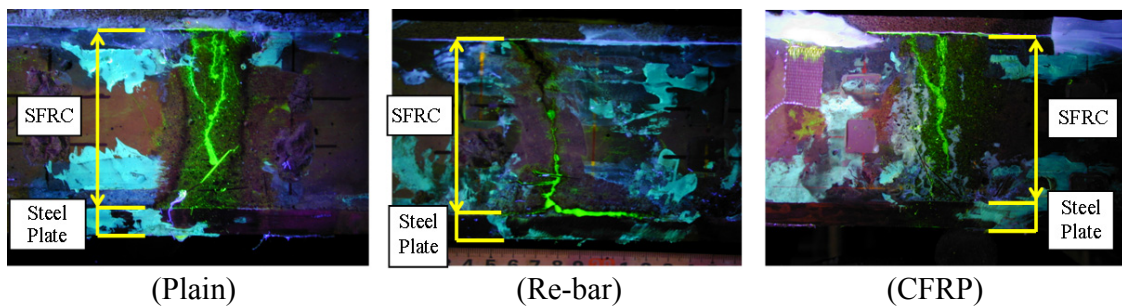
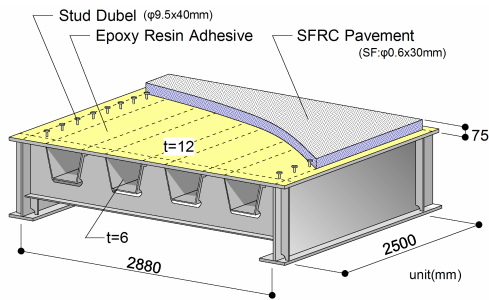


Photo 3 Crack propagations

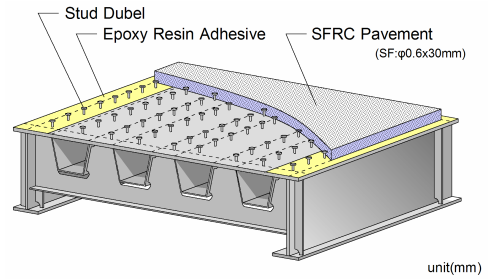
Wheel running test

In order to evaluate durability of SFRC pavement, the tests using partial model mentioned above are not sufficient because their simple structure and fixed point loading cannot recreate complex behaviors of SFRC pavement on OSD. Wheel running test using real size specimen is one of appropriate ways to take for investigating such problems. YBC, one of the member companies of joint research with PWRI had conducted wheel running tests as shown in Photo 4. Two specimens used in the tests are shown in Figure 14, the one is adhesive type and the other is stud type. Having single span of longitudinal rib and two girders at both sides, these were for the durability of SFRC pavement under positive bending. The applied wheel load was 100,000 times (50,000 cycles) of 98kN, 1,000,000 times of 157kN, and then 1,000,000 times of 196kN. Figure 15 shows the changes of live load deformation during 2,100,000 times loading. Deformations increased proportionally with loads and seem not to have any rapid increases. Figure 16 shows longitudinal influence lines of strains at 0.4, 1.1, 2.1 million times. The strains are measured in transverse direction and at 5 mm distant from the toe of trough rib weld on the bottom surface of deck plate. Compressive strains at mid-span of stud type are larger than adhesive type, which indicate that SFRC and deck plate in stud type are not composite in local-wise, probably between studs. However, taking account of 1,200 micro of strain measured before pavement, the stud type has also remarkable stress reduction effect and has maintained it through the test.

One of the biggest problems to be solved is to confirm the durability of cracked SFRC where negative bending moment acts. The research so far has made it clear that crack initiation is inevitable by live load in real situations. Therefore, PWRI's joint research groups are now preparing to conduct another series of wheel running test using real size specimen that has a bracket to cause negative bending. In the test, specimen will be loaded right above the main girder. The effect of water and reinforcement on durability of SFRC and adhesive will also be taken into account. Photo 5 shows the process of SFRC pavement that will be tested. The test is planned to get started in the beginning of 2008.



(a) Adhesive Type



(b) Stud Type

Figure 14 Wheel Running Test Specimens

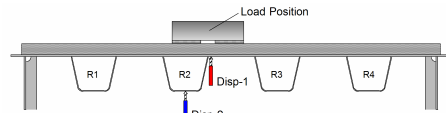
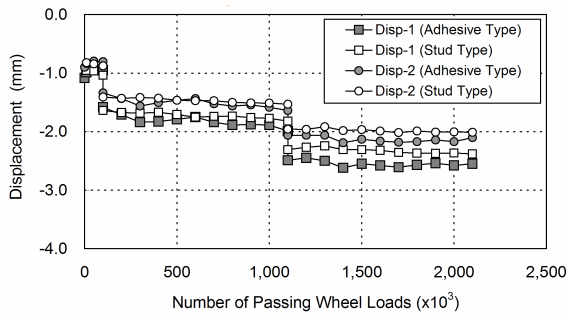


Figure 15 Deformation and Times of Loading

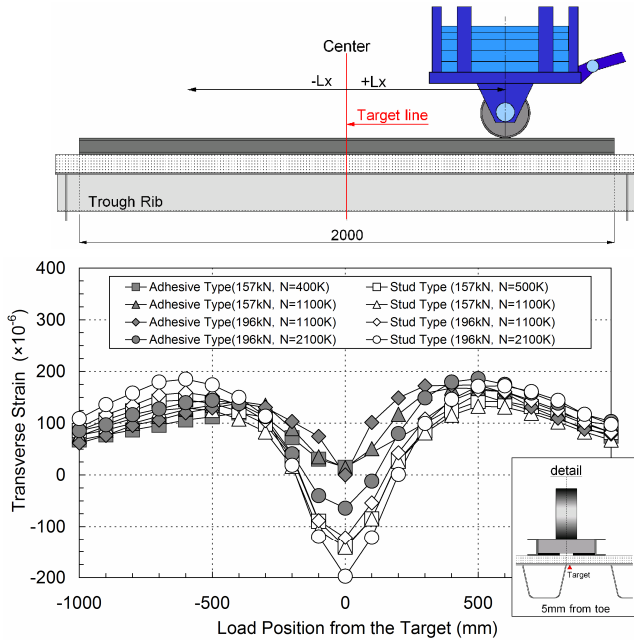


Figure 16 Strains at Bottom Surface of Deck Plate



Photo 4 Wheel Running Test



(a)Brusting



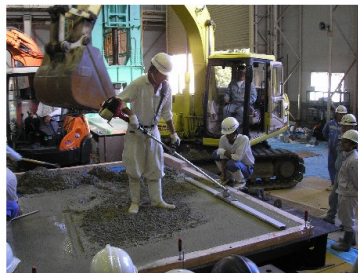
(b)Stud



(c) Adhesive



(d) Reinforcement



(e) Casting



(f) Curing

Photo 5 Pavement Process of Real Size Specimen for Wheel Running Test

Conclusion

SFRC pavement is expected to reduce stress that is related to fatigue crack initiation at the weld between trough ribs and deck plate. The effect has been confirmed both in FE analysis using 3-D models and stress measurement using real size specimens.

For negative bending on SFRC, the effect of reinforcing bars and CFRP were tested in static and fixed point cyclic loading tests. Increase of loads corresponding crack initiations and decrease of crack width are not clear in the specimens using reinforcements, while small differences are observed as to crack width in accordance with rigidities of reinforcement. In the case that a crack penetrated SFRC and water reached the interface between SFRC and steel plate, decrease of tensile strength was observed. However, the decreased area was limited to vicinity of the crack.

Wheel running test showed that SFRC pavement maintained its stress reduction effect through 2,000,000 times loading that caused positive bending in macro-wise on OSD. Another wheel running test focusing on negative bending is being prepared.

Acknowledgments

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