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Structural Behavior of a RC Bridge Slab Retrofitted with Carbon Fiber Sheet under Large Repeated Load

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Abstract

An experimental investigation on the flexural fatigue behavior of a RC bridge slab retrofitted with Carbon Fiber Sheet (CFS) is presented. The test slab was almost identical to the slab of a highway viaduct in terms of the amount of reinforcement, quality of concrete and thickness of the slab, which was 18cm. Repeated load corresponding to 3.0, 4.5 or 6.0 times of the design load was applied to the test slab. Normal type and high-elastic modulus type of CFS were used for strengthening. The test slabs were loaded in dry or wet condition. Two different types of anchoring system were adapted. Some of the test slabs were damaged by the repeated load and retrofitted by CFS, then loaded again to see the improvement of the fatigue life. Infrared Thermography was also performed to investigate the debonding condition of CFS. From the test results, Carbon Fiber Sheet can be applied to the RC bridge slabs as a feasible retrofitting material.

Keywords: fatigue strength, RC bridge slab, carbon fiber sheet

1. Introduction

Recently owing to the increasing of traffic and unexpected heavy traffic load, cracking damages of RC bridge slabs have been found. Fig. 1 shows a traffic survey result[1)] of the number of cars and the weight passed at a section of a highway during continuous 24 hours. According to the result, most of the cars that have passed through the section gave a bending moment less than the design value to the bridge slab.

On the other hand, some cars gave a large bending moment up to 4.5 times of the design load. This excess of loading is considered to be the main reason of the bridge deck slab damages. For the rehabilitation of these damaged bridge slabs, recently developed Carbon Fiber Sheet (CFS) has been applied as a new reinforcing material due to its light weight, high tensile strength, and easy application.

Many researchers[2-4)] have investigated the effectiveness of CFS for flexural strengthening of RC members under static loading. Also, Kaiser,[5)] Hoshijima et al[6)] and Barnes et al[7)] examined the fatigue performance of CFRP strengthened RC members. However, the research on the fatigue behavior of RC Bridge slab retrofitted with CFS has not been reported so much, particularly under very heavy load. Therefore, this study is mainly planed to clarify the fatigue behavior of RC bridge slab retrofitted with CFS under large repeated loading.

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2. Experiment

According to the report of Hansin Expressway,[8)] cracks develop both in the parallel and perpendicular direction of a slab. Therefore, the CFS should be applied in the both directions to retrofit the slab efficiently. However, only one directional behavior of the slab was studied in this research.

2.1 Test slab

Fig. 2 shows the test slab and cross section. A total of 21 specimens were constructed. The overall length of the test slab was 2000 mm, the thickness was 180 mm and the width was 370 mm which was 2 times of the thickness. The test slab was almost identical to the real slab of a highway in terms of the amount of steel reinforcement, quality of concrete and the thickness of the slab. This test slab repre-

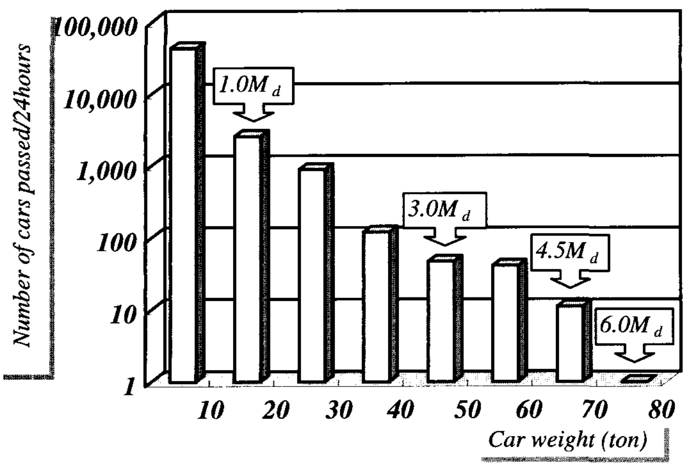
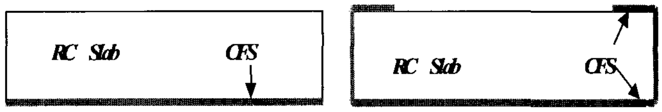


Fig. 1 Car survey result in a highway



(a) Normal Anchor (NA) (b) Perfect Anchor (PA)

Fig. 3 Anchoring system

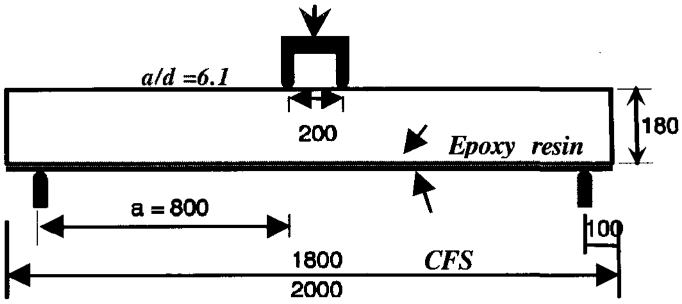


Fig. 4 Loading set-up

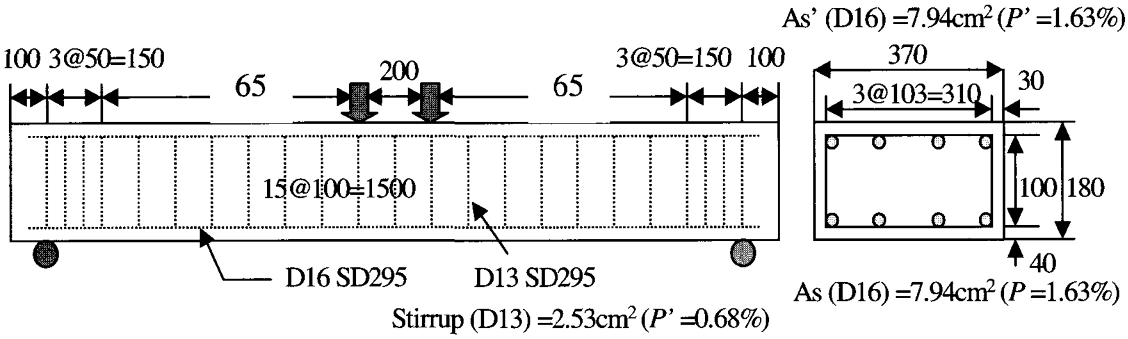


Fig.2 Test slab and cross section (mm)

sented a part of the real slab with the same flexural moment capacity. Also, in order to avoid shear failure stirrup was arranged. Some test slabs were damaged by fatigue loading up to 90 % of maximum cycle numbers of control slab before strengthening.

2.2 Material properties

Ready-mixed concrete was used for all test slabs. The concrete had a water-cement ratio of 0.45 by weight, and the maximum aggregate size was 20 mm. Concrete cylinders (100×200 mm) were cast and tested to determine the concrete compressive strength. The unidirectional CFS was used for strengthening. The properties of the materials used in this study are summarized in Table 1. Normal type of CFS with 300 g/m^2 (T300), 400 g/m^2 (T400) and high-elastic modulus type of CFS with 300 g/m^2 (HM300) were used for the strengthening. The CFS was glued at the bottom of the test slabs with 370 mm width by Normal Anchoring(NA) or Perfect Anchoring (PA) as shown in Fig. 3.

2.3 Loading set-up

Fig. 4 shows the loading set up. All test slabs were simply supported and subjected to two concentrated loads symmetrically placed about the mid-span. Flexural fatigue test with 6.1 shear-span ratio (a/d) was conducted under four-point flexural cyclic load. The cyclic load was applied by 1.0 Hz to yield 3.0M$_d$, 4.5M$_d$ and 6.0M$_d$ at the span center, respectively. Design flexural moment suggested by Hansin Expressway Co. was applied, and which was 29.4 kN-m/m. In this paper, M$_d$ is corresponding design flexural moment for the specimen width of 0.37 m(= 10.9 kN-m).

2.4 Measurement & test procedures

At various positions along the slabs span, electrical resistance strain gauges were attached to measure the strains on the tensile reinforcement, the bottom of the CFS and the extreme compression face of the test slab. The deflection was also measured by Linear Variable Displacement Trans-

Table 1 Properties of material used

Material	Properties					
Concrete	Compressive strength: 39.2 N/mm^2 Elastic modulus: 3.92x10^4 N/mm^2 Tensile strength: 3.4 N/mm^2					
Steel	Longitudinal reinforcing: D16 Yield strength: 341 N/mm^2					
Epoxy	Elastic modulus: 2.3x10^3 N/mm^2 Tensile strength: 55.3 N/mm^2					
CFS	Weight (g/m^2)	Density (g/cm^3)	Thickness (mm)	Tensile strength (N/mm^2)	***Elastic modulus (N/mm^2)***	Rupture strain (μ)
T 300 T 400	300 400	1.8	0.167 0.222	3430	***2.53 x 10^5***	14900
HM 300	300	1.82	0.165	2940	***3.92 x 10^5***	7500

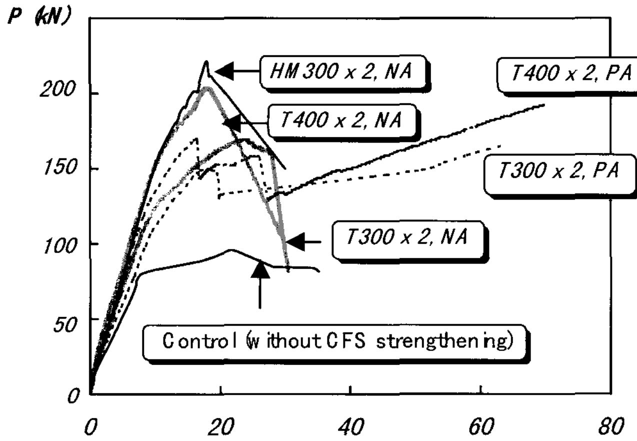


Fig. 5 Load - displacement curves at the span center

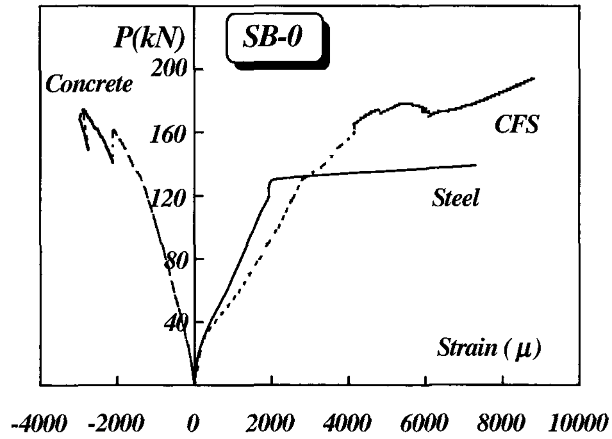


Fig. 6 Load - strain curves (T400x2)

ducer (LVDT) placed at the center of the slab.

Measurement of the strain and displacement of the test slab was performed under static load after certain cycles of repeated loading. The magnitude of the statically applied load was limited up to the same magnitude as the present not fail by fatigue were tested under static load in order to cyclic load. The test slabs that did certify their residual flexural strength.

3. Results of the test

3.1 Static test results

Fig. 5 and Fig. 6 show the load-deflection and load-strain curves of the test slabs, respectively. The failure procedures of retrofitted slab by CFS are regarded as follows. First, after occurring the first cracks in the concrete, the stiffness was reduced. From that time, the tensile steel and CFS were beginning to receive the additional load directly, and the behavior of these materials were almost linearly continued until the tensile steel was yielded nearly the strain of 2000 μ. After yielding of the tensile steel, with the additional changes of stiffness and deflection, CFS only received the additional tension stress.

After all, the failure of retrofitted slabs mainly occurred by debonding of interface between concrete and CFS, and the large deflections were continuously taken place in the slabs. From the static test results, retrofit of the test slab with 2 layers of HM300 CFS improved the flexural strength up to 2.4 times.

3.2 Fatigue test results

3.2.1 Typical failure mode

Table 2 is the summary of the fatigue test results. Fig. 7 shows the typical failure pattern of retrofitted test slabs with CFS. Almost the same failure mode at static test was happened in the fatigue test. Failure occurred immediately after debonding of CFS from concrete and crushing of concrete in the compression zone followed at the same time. This failure pattern indicates that the bond strength between concrete and CFS is one of the important factors to decide the actual strength of the retrofitted slab. While, the place where shear force is zero, CFS was still attached in the Perfect Anchored slab. The control slabs without CFS failed at 0.46 million cycles in dry condition and 0.33 million cycles

Table 2 Fatigue test results

CFS (2 Layers)	Anchor type	Test slab	Load level	Number of cycles at failure	Flexural strength	
					Before repeated loading	After repeated loading
No CFS	Control		$3.0M_d$	$n_{max}=4.6\times10^5$	(Dry condition)	
				$n_{max}=3.3\times10^5$	(Wet condition)	
T300 ($300g/m^2$)	PA	SA - 0	Static		$5.94M_d$	
		FA - 1	$3.0M_d$	9.50×10^5		
		FA - 2	$4.5\ M_d$	6.60×10^4		
		FA - 3	$6.0\ M_d$	7.63×10^3		
T400 ($400g/m^2$)	PA	SB - 0	Static		$6.97M_d$	
		FB - 1	$3.0M_d$	over 5.0×10^6		$6.49M_d$
		FB - 2	$4.5M_d$	3.03×10^5		
		FB - 3	$6.0M_d$	1.10×10^4		
	NA	SC - 0	Static		$7.27M_d$	
		FC - 1	$3.0M_d$	over 2.0×10^6		$7.19M_d$
		FC - 2	$4.5M_d$	4.30×10^5		
		FC - 3	$6.0M_d$	2.76×10^4		
		FD*1-1	$3.0M_d$	over 2.0×10^6		$6.24M_d$
		FE*2-1	$3.0M_d$	over 2.0×10^6		$7.70M_d$
		FF*3-1	$3.0M_d$	over 2.0×10^6		$5.94M_d$
HM300 ($300g/m^2$)	NA	SG - 0	Static		$7.99M_d$	
		FG - 1	$3.0M_d$	over 3.0×10^6		$7.89M_d$
		FG - 2	$4.5M_d$	over 3.0×10^6		$7.89M_d$
		FG - 3	$6.0M_d$	1.85×10^4		

M_d = The design flexural moment, which corresponds to 10.9 kN-m for the test slab.

M_{max} of the control slab without CFS was 36.7 kN-m (=3.37 M_d)

*1 : FD-1 specimen was loaded until $n = 2.3\times10^5$ (50% of n_{max}) cycles before retrofitting by CFS

*2 : FE-1 specimen was loaded until $n = 4.2\times10^5$ (90% of n_{max}) cycles before retrofitting by CFS

*3 : FF-1 slab was loaded under wet condition

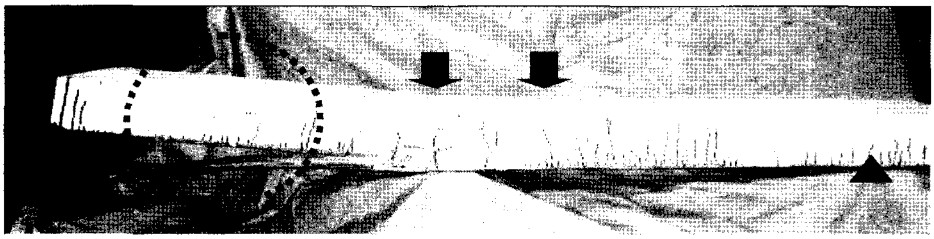


Fig. 7 Typical debonding failure (Normal anchor)

in wet condition both under $3.0M_d$. These slabs showed flexural failure with the breaking of tensile steel reinforcement. All test slabs retrofitted by 2 layers of T300 CFS showed debonding failure by fatigue. However, the FB-1 and FC-1 slabs retrofitted by 2 layers of T400 CFS both under the load of $3.0M_d$ did not fail at the specified cycles. They were loaded statically until failure. After static test, FB-1 slab maintained 93 % of the initial flexural strength even after application of 5.0 million cycles of the $3.0M_d$. However, the other test slabs retrofitted by 2 layers of T400 CFS failed under the repeated load of $4.5M_d$.

3.2.2 Effect of anchoring system

Energy-absorbing characteristics denoted by deflection ductility was developed to investigate the structural behavior of two different anchoring systems.

$$\textit{Deflection ductility} = \frac{\delta_u}{\delta_y} \qquad (1)$$

where δ_y is the deflection at the span center when the tensile steel yielded

δ_u is the deflection at the span center when the applied load dropped down to the level of yielding load from the maximum

From the static test results, Perfect Anchor (PA) contributed to the improvement of the slab ductility as shown in Fig 8. Therefore, this fact should be taken into consideration for the practical application. However, there was al-

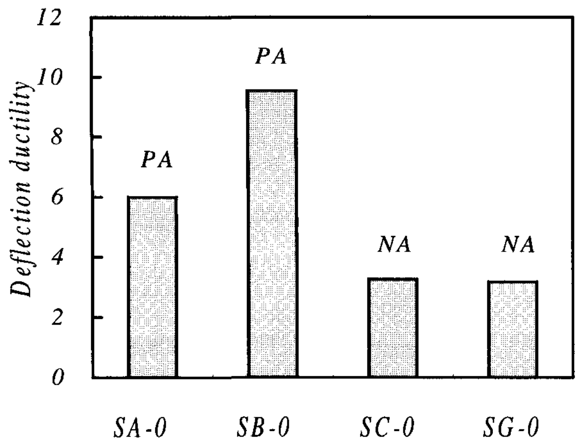


Fig. 8 Ductility improvement due to anchoring

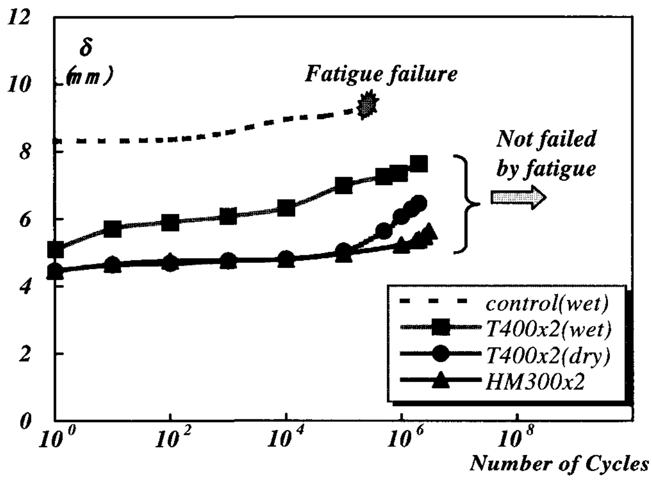


Fig. 9 Deflection of HM series slab

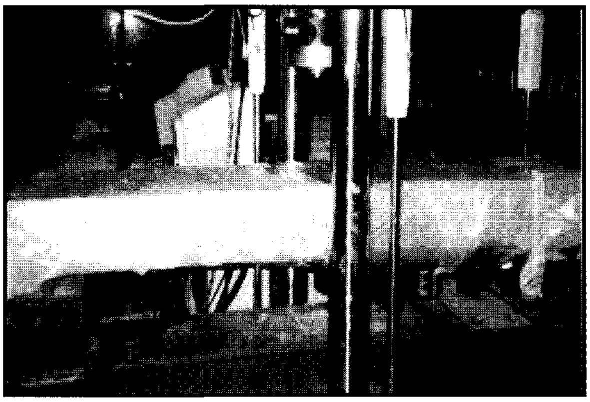


Fig. 10 Fatigue test under wet condition

most no difference in load carrying capacity between two anchoring systems.

In fatigue test, however it was not easy to explain the delamination phenomenon of different anchoring systems. From the residual flexural strength of test slabs which did not fail by fatigue, maximum cycle numbers of fatigue failed slabs and variation of flexural stiffness, it could be seen that there was no large difference between normal and perfect anchored slabs in fatigue life.

3.2.3 Effect of high elastic modulus of CFS

On the other hand, within the scope of this research, the most significant factor contributing to the improvement of fatigue behavior of retrofitted slab was high elastic modulus of CFS. The same phenomenon was also appeared in the experiment of Hoshijima et al.[6] They conducted a wheel trucking fatigue test with damaged RC deck slab strengthened by CFS. From the results, the damaged RC deck slab prolonged its fatigue life more than 5 to 17 times owing to the CFS, and also the high elastic modulus of CFS was considered as more effective for extending fatigue life of existing bridge slab.

The test slabs FG-1 and FG-2 retrofitted with high elastic modulus of CFS exhibited a significant effect to elongation of fatigue life and restraint of deflection as shown in Fig. 9. Especially, the test slab FG-2 strengthened by 2 layers of HM300 CFS still maintained almost the same flexural strength even after the application of 3.0 million cycles of $4.5M_d$. Therefore, this amount of CFS is recommended to retrofit of highway bridge slab.

3.2.4 Pre-damaged slab

Even badly damaged slab could be recovered its fatigue strength by the application of CFS. The test slabs FD-1 and FE-1 were loaded until 50 % and 90 % of the failure cycles of control slab, respectively. Then, they were retrofitted by 2 layers of T400 CFS. After retrofitting, they were loaded again under the load of $3.0M_d$ until 2.0 million cycles.

However, they did not fail by fatigue and possessed enough flexural strength even after the application of the cyclic load. Therefore, it is still significant to retrofit a RC Bridge slab by CFS even if it is already heavily damaged.

3.2.5 Fatigue test under wet condition

The control slab without CFS failed at 0.33 million cycles in wet condition under $3.0M_d$. The test slab FF-1was retrofitted by 2 layers of T400, and then submerged for one month before fatigue test. Prior to repeated loading, this slab was wound by a vinyl wrapper to prevent evaporation of water and to conserve the wet condition during the test as shown in Fig. 10. From the test results, this slab increased its fatigue life from 0.33 millions cycles to over 2.0 million cycles due to the application of CFS.

3.2.6 S-N curves

Fig. 11 shows the S-N curves of the test slabs. The fatigue life of retrofitted slab was increased with the increase

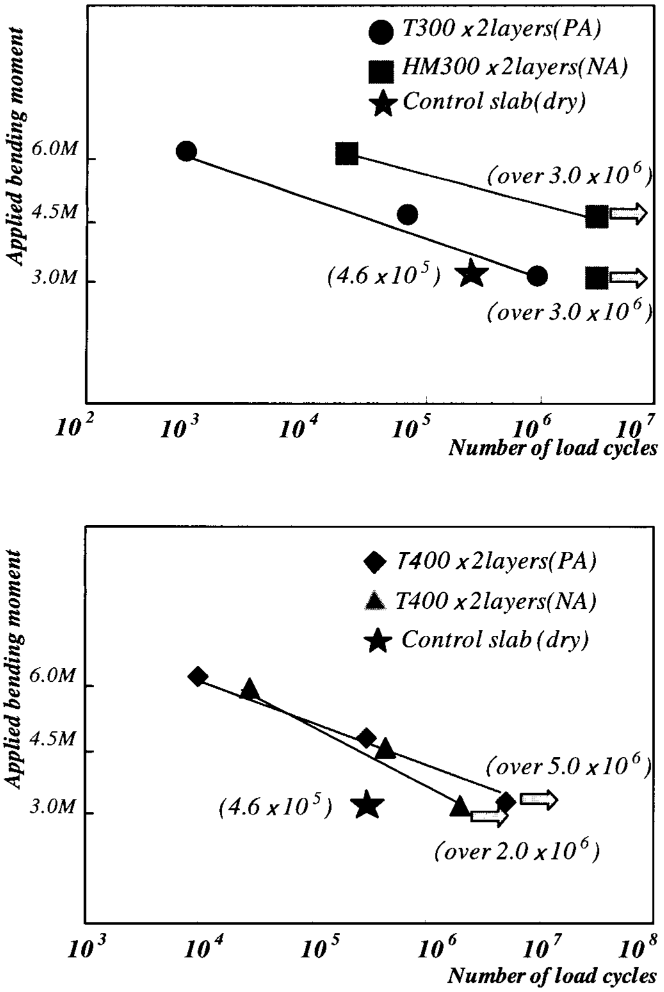


Fig. 11 S-N curves

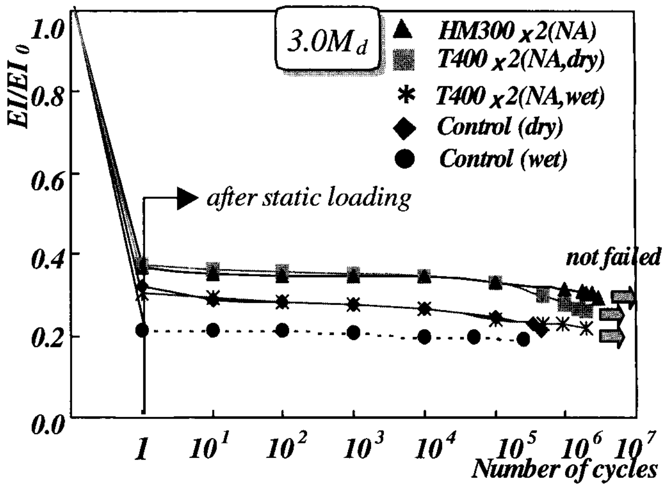


Fig. 12 Degradation of stiffness due to fatigue

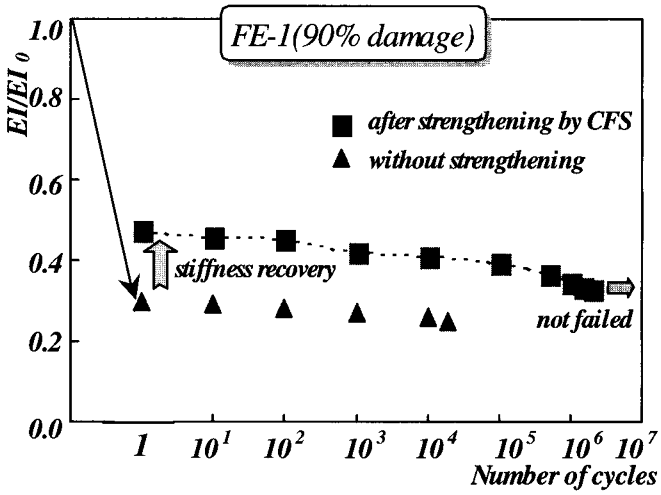


Fig. 13 Stiffness recovery due to CFS

of the amount of CFS. The slab retrofitted by 2 layers of T300 CFS failed by fatigue even under the applied load of $3M_d$. However, the retrofitted RC slabs with 2 layers of T400 CFS prolonged its fatigue life over 5.0 times in wet condition, and 10 times in dry condition under 3.0 M_d.

3.3 Variation of the flexural stiffness

Fig. 12 shows the variation of the flexural stiffness due to fatigue. The flexural stiffness of the test slabs after each cycle of repeated loading was evaluated as follows;

Before loading

$(EI)_0$ = based on the gross section by calculation

After loading

$$EI = \frac{P}{\delta}\left(\frac{aL^2}{16} - \frac{a^3}{12}\right) \qquad (2)$$

Where, δ : deflection at the slab center,
a: shear span (=800 mm)
L: length of the span (=1800 mm)

The stiffness of the slab retrofitted by 2 layers of T400 CFS dropped to 62 % of the initial value under the application of the static load of $3M_d$. However, the loss of the stiffness under the cyclic loading was gradual and even after the 2.0 million cycles of $3M_d$ the slab still maintained 71 % of the initial stiffness value just after the static loading of $3M_d$.

On the other hand, the test slab FE-1 pre-damaged up to 90 % of the failure cycle numbers of control slab recovered its flexural stiffness up to 50 % due to the application of 2 layers of T400 CFS as shown in Fig. 13. This slab also still maintained 67 % of the initial recovered stiffness value after the 2.0 million cycles of $3.0M_d$ loading.

3.4 Total dissipated energy capacity

The energy dissipation characteristic of a laminated RC slab by CFS was investigated. The total dissipated energy capacity E_{total} gained from the total area under the load-deflection curve (P- δ curve) as shown in Fig. 14 was defined as follows;

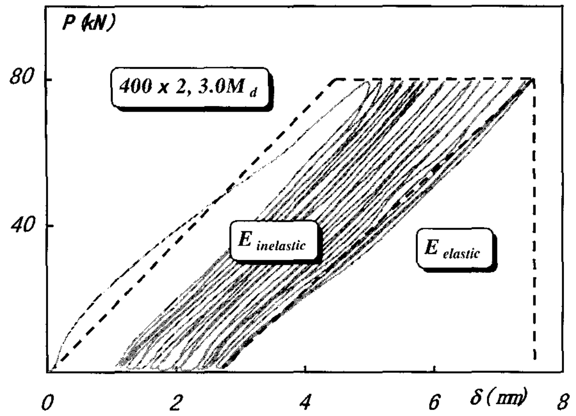


Fig. 14 Definition of total dissipated energy capacity

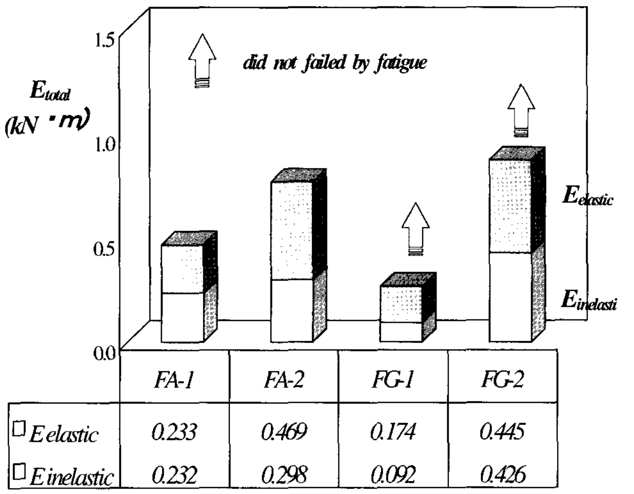


Fig. 15 Total dissipated energy capacity

$$E_{total} = E_{inelastic} + E_{elastic} \qquad (3)$$

where, $E_{inelstic}$ is the inelastic energy cumulated before failure
$E_{elastic}$ is the elastic energy released at failure

Fig. 15 shows the total dissipated energy capacity E_{total} of each test slab during repeated loading. The effect of CFS on the total dissipated energy capacity was very similar to that on fatigue life. It could be seen that the variation of the total energy was dependent on the CFS. In other words, the total energy dissipation capacity of retrofitted slabs under repeated loading was increased with the increase of the amount of CFS.

On the other hand, the significant factor contributing to the total energy capacity was high elastic modulus of CFS. For example, FA-1 slab retrofitted with 2 layers of T300 CFS failed at 0.95million cycles with the inelastic cumulative energy of 0.232 kN·m.

But, FG-1 slab retrofitted with 2 layers of HM300 CFS possessed about 2.5 times less inelastic energy 0.092 kN·m

Fig. 16 Infrared Thermography testing

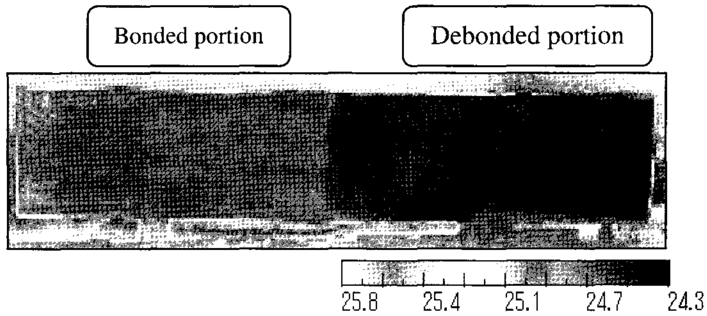


Fig. 17 Variation of temperatures by Infrared Thermography

even after the application of 3.0 million cycles of the same load level. This phenomenon indicates that the high elastic modulus type of CFS gives a much significant effect on delaying the rate of the fatigue damage accumulation.

It may be also supposed that the amount of the elastic energy E_{elstic} released at failure increases due to the increase of the elastic modulus of CFS. But, because of the limited data obtained so far, it is premature to explain clearly. Further experimental investigations are necessary to validate the real phenomenon of laminated composite members on dissipated energy capacity.

4. Applications of Infrared Thermography

Infrared Thermography is a well-established tool in the field of Non-Destructive Testing and monitoring techniques for investigating deterioration levels of existing structures.

In order to investigate the debonding phenomenon and exfoliation condition of CFS, Infrared Thermography test was performed. The exfoliation conditions of CFS from the concrete surface could be inspected by collected temperature (actually, amount of infrared rays) radiated from the concrete surface as shown in Fig. 16~17. From the results, the Infrared Thermography can be applicable to inspect the exfoliation conditions of retrofitted RC structures by CFS.

5. Conclusions

Based on the experimental results, the following conclusions can be drawn.

(1) The failure of retrofitted slabs mainly occurred by debonding of CFS from the concrete surface. This failure pattern indicates that the improvement of bond strength between concrete and CFS may increase the fatigue strength of the slab more.

(2) From the static test, retrofit of the test slab with 2 layers of HM300 CFS improved the flexural strength up to 2.4 times.

(3) The test slab laminated by 2 layers of T400 CFS lasted more than 5 millions cycles of the 3 times design load, whereas the test slab without CFS failed at about 0.46 millions cycles under the same loading.

(4) The test slab with 2 layers of HM300 CFS had kept the same initial flexural strength even after the application of 3million cycles of the 4.5 times design load.

(5) Even badly damaged slabs and wetted slab recovered its fatigue strength by the application of CFS. Therefore, it is still significant to retrofit a RC bridge slab by CFS even if it is already heavily damaged.

(6) Good anchoring improved the ductility of the retrofitted slab. This fact should be taken into consideration for the practical application.

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