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Flexural Fatigue Strength of a RC Bridge Slab Laminated by Carbon Fiber Sheets

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An experimental investigation on the flexural fatigue behavior of a RC bridge slab retrofitted with Carbon Fiber Sheet [CFS] is presented. The test slab is 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 is 18cm. Repeated load corresponding to 3.0, 4.5 or 6.0 times of the design load was applied to the test slab until failure. The main results obtained from the test are as follows:

(1) Fatigue failure of the slab occurred mainly due to delamination of the CFS.
(2) The composite test slab laminated by 2 layers of T400 CFS lasted under 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.
(3) The test slab strengthened by 2 layers of HM300 CFS still maintained almost the same flexural strength even after the application of 3.0 million cycles of 4.5 M_d.
(4) Even badly damaged slab recovered its fatigue strength by the application of CFS.

Key Words: Fatigue strength, RC bridge slab, Carbon fiber sheet,

1. Introduction

Recently owing to the increasing of traffic and unexpected heavy traffic load, cracking damages[1] of RC bridge slabs have been found in many highway as shown in Figure 1. Figure 2 shows a survey result [2] 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 value. This excess of loading is considered to be the main reason of the damage. For the rehabilitation of these damaged bridge slabs, recently developed Carbon Fiber Sheet [CFS] has been successfully played key roles as a feasible reinforcing material due to its light weight, high tensile strength, and easy application.

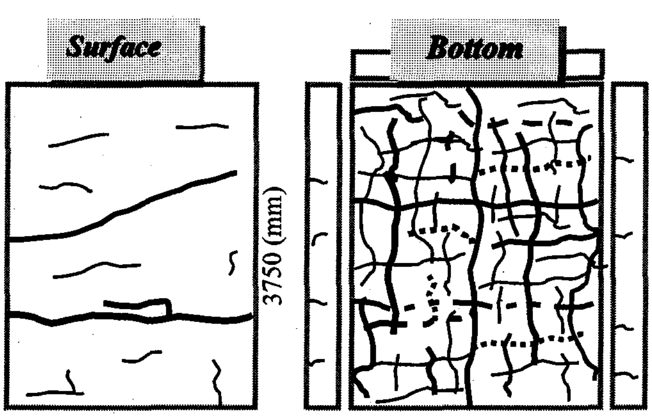


Fig.1 Damages to a highway bridge slab

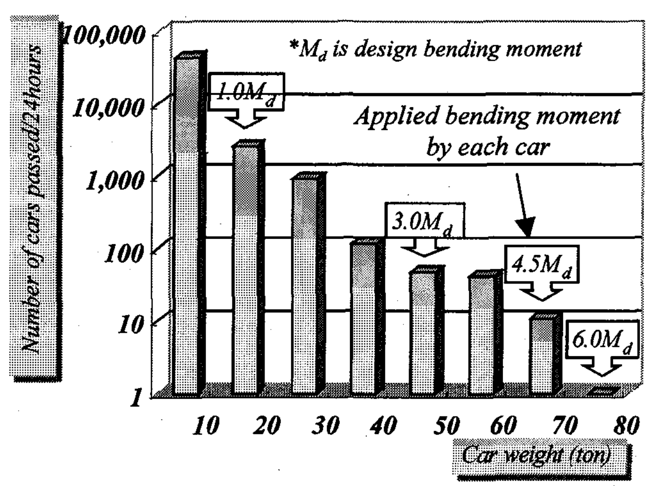


Fig. 2 Car survey result in a highway

Many researchers [3) 4) 5) 6)] have investigated the effectiveness of CFS for flexural strengthening of RC members under static loading. Also, Kaiser[7)], Hoshijima et al[8)] and Barnes et al[9)] examined the fatigue performance of CFRP strengthened RC members. However, the research[10)] on the fatigue behavior of RC bridge slab laminated by 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 by CFS under very large repeated loading.

2. Experiment

According to Figure 1, cracks develop both in the parallel and perpendicular direction of a slab. Therefore, 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

Figure 3 shows the test slab and cross section. A total of 19 slab specimens were constructed. The overall length of the test slab is 2000mm, the width is 370 mm and the thickness is 180mm. The test slab is 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 represents a part of the real slab with the same flexural moment capacity. 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 20mm. Concrete cylinders (100x200mm) were cast and tested to determine the concrete compressive strength. The unidirectional CFS was used for strengthening.

Normal type of CFS with 300g/m^2 (T300), 400g/m^2 (T400) and high-elastic modulus type of CFS with 300g/m^2 (HM300) were used for the strengthening. CFS was glued at the bottom of the test slabs with Normal (NA) or Perfect Anchoring (PA) as shown in Figure 4. The properties of the materials used in this study are summarized in Table 1.

2.3 Loading Set-up

Figure 5 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 1.0Hz to yield 3.0M_d, 4.5M_d and 6.0M_d at the span center, respectively, where M_d is the design flexural moment.

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 Transducer (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 cyclic load. The test slabs that did not fail by fatigue were tested under static load in order to certify their residual flexural strength.

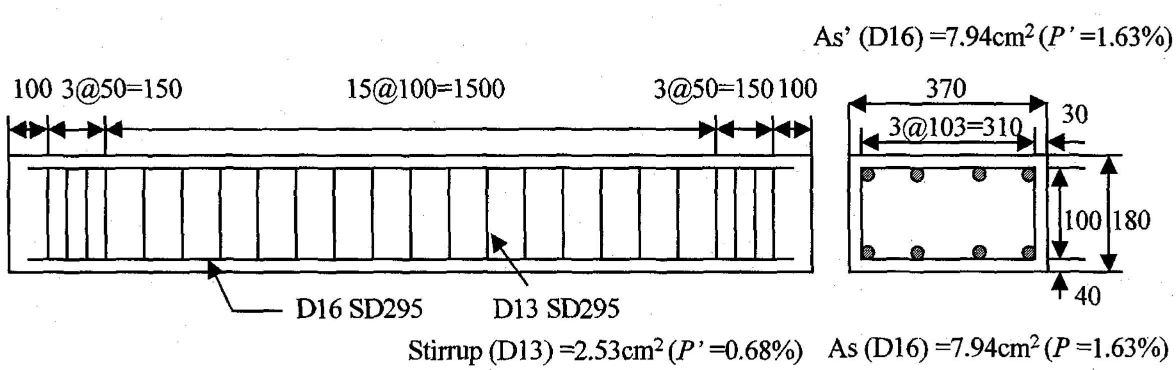
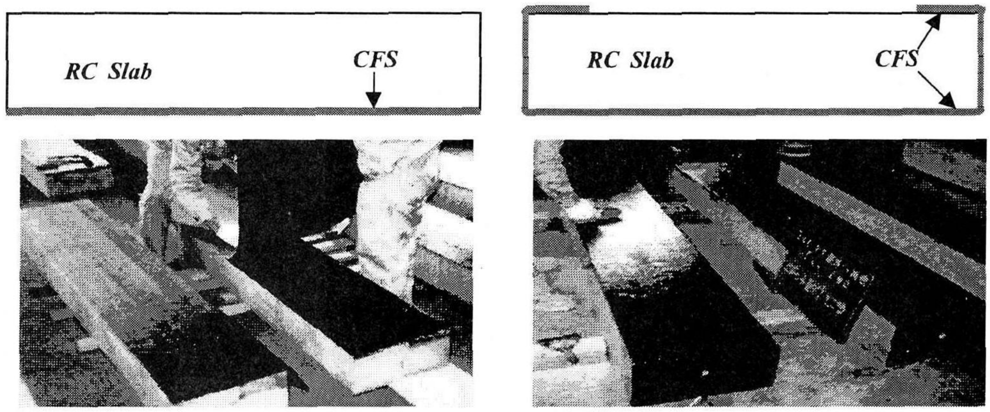


Fig. 3 Test slab and the cross section (mm)

Table 1. Properties of material used

Material	Properties					
Concrete	Compressive strength : 39.2 N/mm^2 Elastic modulus : 3.92×10^4 N/mm^2 Tensile strength : 3.4 N/mm^2					
Steel	Longitudinal reinforcing : D16 Yield strength : 341 N/mm^2					
Epoxy	Elastic modulus : 2.3×10^3 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	300	1.8	0.167	3430	***2.53 x 10^5***	14900
T 400	400		0.222			
HM 300	300	1.82	0.165	2940	***3.92 x 10^5***	7500



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

Fig. 4 Anchoring type

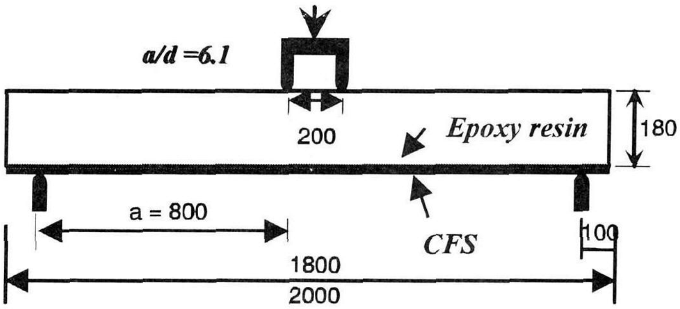


Fig. 5 Loading Set-up

3. Results of the Test & Discussion

3.1 Static Test Results

Figure 6 and Figure 7 show the load-deflection and load-strain curves of the test slabs, respectively. The failure procedures of retrofitted test 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 2000μ . 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.

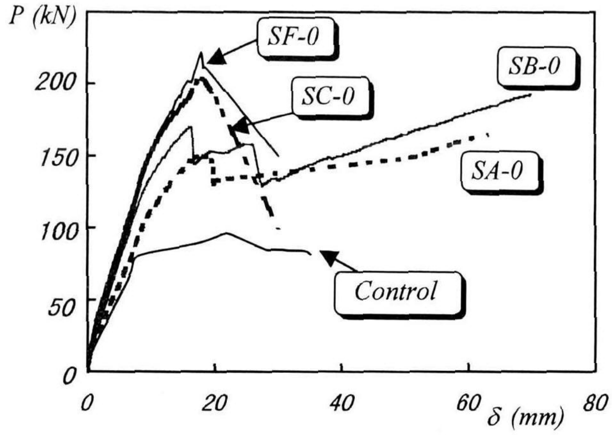


Fig. 6 Load - displacement curves at the span center

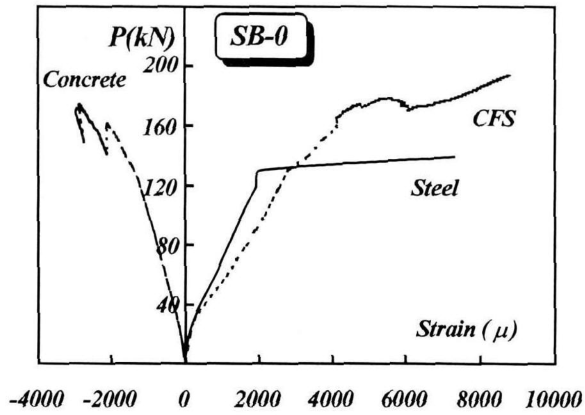
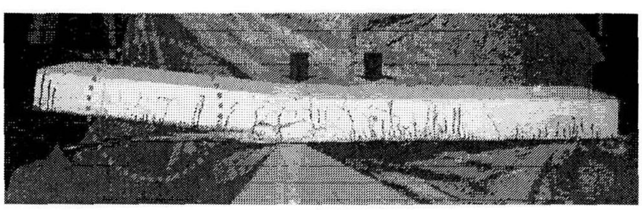


Fig. 7 Load - strain curves

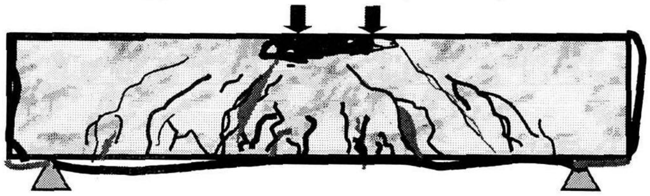
3.2 Fatigue Test Results

3.2.1 Typical Failure Mode

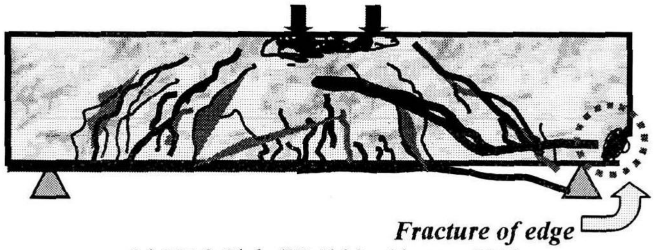
Table 2 is the summary of the fatigue test results. Figure 8 shows the typical failure pattern of retrofitted test slabs with CFS. Almost the same failure mode as static test was happened in the fatigue test. Failure occurred immediately after debonding of CFS from concrete and crushing of concrete in the compression zone followed at the same time.



(a) FC-1 slab (T400× 2layers, NA)



(b) FA-1 slab (T300× 2layers, PA)



(c) FF-3 Slab (HM300× 2layers, NA)

Fig. 8 Typical debonding failure

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 as shown in Figure 8-(b).

The control slab failed at 4.6×10^5cycles under the load of $3.0M_d$. This slab showed flexural failure with the breaking of 2 tensile steel reinforcement. All test slabs retrofitted by 2layers of T300 CFS showed debonding failure by fatigue. However, the test slab FB-1 retrofitted with 2layers of T400 CFS did not fail by fatigue load even after application of 5 million cycles of the $3.0M_d$. This test slab was loaded statically until failure. Finally, the FB-1slab maintained 93% of the initial flexural strength even after application of 5 million cycles of the $3.0M_d$. The failure characteristic of different anchored slabs will be discussed in the section 3.2.3.

3.2.2 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 is high elastic modulus of CFS. The same phenomenon was also appeared in the experiment of Hoshijima[8] et al. 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 FF-1 and FF-2 retrofitted with high elastic modulus of CFS exhibited a significant effect to elongation of fatigue life and restraint of deflection as shown in Figure 9. Especially, the test slab FF-2 strengthened by 2 layers of HM300 CFS still maintained almost the same flexural strength even after the application of 3.0million cycles of 4.5M_d.

Therefore, this amount of CFS is recommended to retrofit of highway bridge slab. However, sufficient considerations like end anchorage are required to avoid brittle failure pattern as shown in Figure 8-(c).

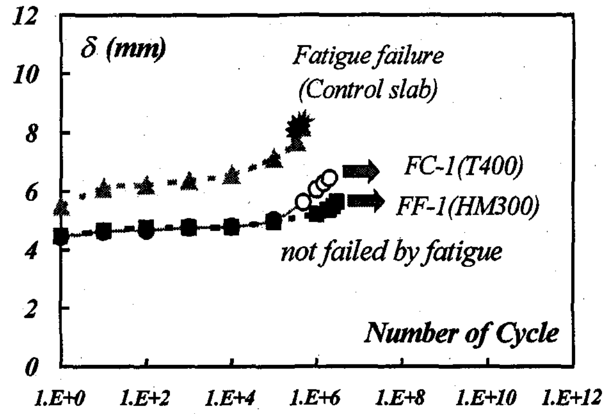


Fig. 9 Deflection vs. number of cycle curves

Table 2. Fatigue test results

CFS	Anchoring type	Test slab	Applied load level	Number of cycles at failure	Flexural strength	
					Before repeated loading	After repeated loading
No CFS	Control		3.0M_d	$n_{max} = 4.6 \times 10^5$		
T300 (300g/m^2) 2 Layers	PA	SA−0			5.94 M_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) 2 Layers	PA	SB−0			6.97 M_d	
		FB−1	3.0M_d	over 5.0×10^6		6.49 M_d
		FB−2	4.5M_d	3.03×10^5		
		FB−3	6.0M_d	1.10×10^4		
	NA	SC−0			7.27 M_d	
		FC−1	3.0M_d	over 2.0×10^6		7.19 M_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		6.24 M_d
		FE−1*2	3.0M_d	over 2.0×10^6		7.70 M_d
HM300 (300g/m^2) 2 Layers	NA	SF−0			7.99 M_d	
		FF−1	3.0M_d	over 3.0×10^6		7.89 M_d
		FF−2	4.5M_d	over 3.0×10^6		7.89 M_d
		FF−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 slab was loaded until $n = 2.3 \times 10^5$ (50% of n_{max}) cycles before retrofitting by CFS
- *2 : FE-1 slab was loaded until $n = 4.2 \times 10^5$ (90% of n_{max}) cycles before retrofitting by CFS

3.2.3 Effect of Anchoring System

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

$$Deflection\ ductility = \frac{\delta_u}{\delta_y}$$

* δu is the deflection at the span center when the applied load dropped down to the level of yielding load from the maximum
* δy is the deflection at the span center when the tensile steel yielded

From the static test results, Perfect Anchoring (PA) contributes to the improvement of the slab ductility as shown in Figure 10. Therefore, this fact should be taken into consideration for the practical application. However, there was almost no difference in load carrying capacity between two anchoring types.

In fatigue test, however it was not easy to explain the delamination phenomenon of different anchored slabs at failure. From the results of residual flexural strength of the test slabs which did not fail by fatigue, maximum cycle numbers of fatigue failed slabs and variation of flexural stiffness as shown in Figure 12, it was considered that there was no large difference between PA and NA slabs in fatigue life.

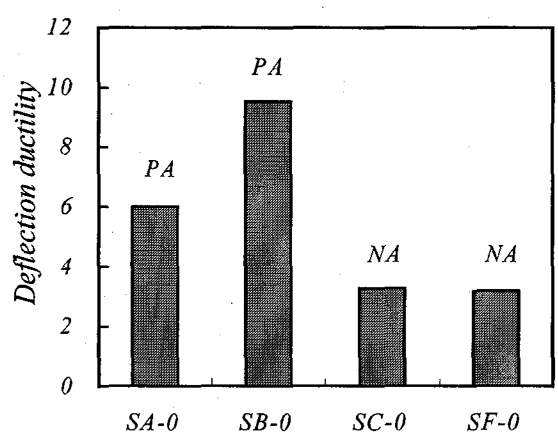


Fig. 10 Ductility improvement due to anchoring

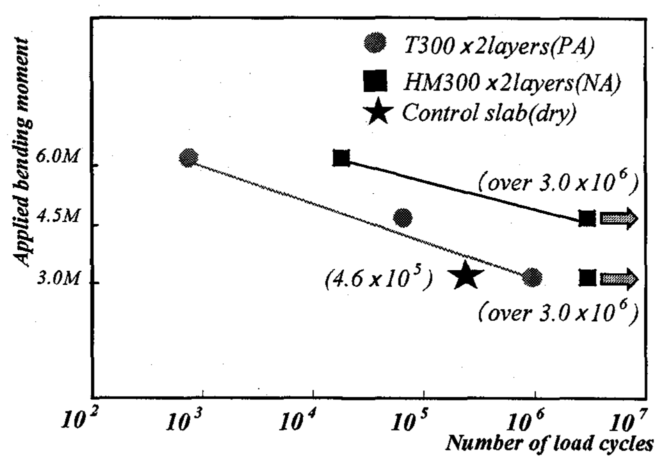
3.2.4 Pre-damaged Slab

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 2layers of T400 CFS. After retrofitting, they were again loaded under the load of $3.0M_d$ until 2.0 million cycles.

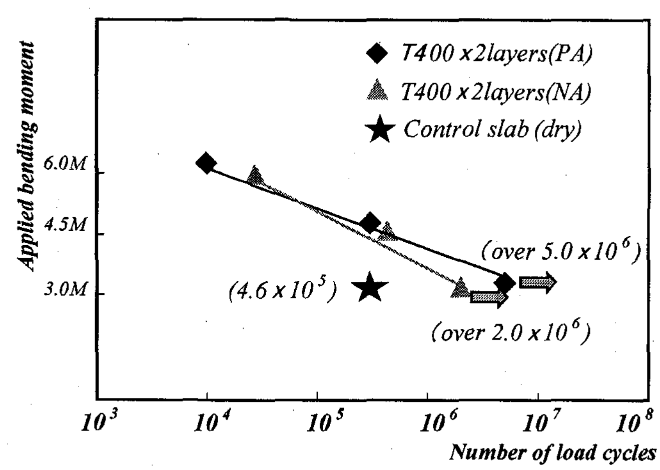
However, they did not fail by fatigue and possessed enough flexural strength even after the application of the cyclic load. Therefore, it is still significant to retrofit a RC bridge slab by CFS even if it is already heavily damaged.

3.2.5 S-N curves

Figure 11 shows the S-N curves for the test slabs. The fatigue life of retrofitted slab increased with the increase of the amount of CFS. The slabs retrofitted by 2 layers of T300 CFS failed by fatigue even under the applied load of $3M_d$. However, the slabs retrofitted by 2layers of T400 CFS did not fail by fatigue under the load of $3.0M_d$, and had more than 10times longer fatigue life compared to the control slab.



(a) Slab with $300g/m^2$ CFS



(a) Slab with $400g/m^2$ CFS

Fig. 11 S-N Curves

3.3 Variation of the Flexural Stiffness

Figure 12 shows the variation of the flexural stiffness due to fatigue. The flexural stiffness of the test slab after each cycle of repeated loading is evaluated by follows;

- Before loading

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

- After loading

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

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 2layers 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 Figure 13.

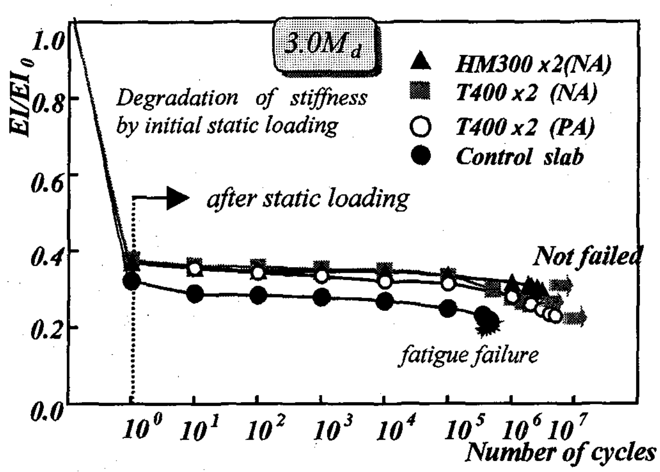


Fig. 12 Loss of stiffness due to Fatigue

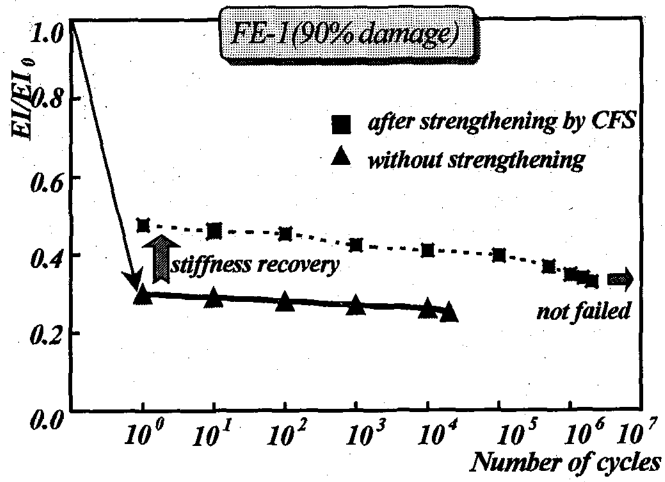


Fig. 13 Stiffness recovery due to CFS

4. Conclusions

Based on the experimental results presented herein, the following conclusions are 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) The test slab laminated by 2 layers of T400 CFS lasted more than 5millions cycles of the 3 times design load, whereas the test slab without CFS failed at about 0.46 millions cycles under the same loading.
(3) 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 4.5times design load. Therefore, this amount of application is recommended to retrofit of highway bridge slab.
(4) Even badly damaged slab recovered its fatigue strength by the application of CFS.

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