- Technical Paper -

APPLICATION OF AFS IN STRENGTHENING OF DETERIORATED RC BRIDGE SLABS SUBJECTED TO WHEEL LOAD

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ABSTRACT
Strengthening of reinforced concrete (RC) structures with fiber reinforced plastics has become an increasingly popular method. In this research, the effectiveness of aramid fiber sheet (AFS) in strengthening RC bridge slabs subjected to fatigue wheel load is investigated. The specimens were subjected to initial damage before bonding of AFS in grid pattern. Fatigue tests by using wheel running machine were conducted. Experimental results reveal that the AFS is capable in improving the fatigue durability by expanding the service lifespan of non-strengthened slab.
Keywords: aramid fiber sheet, RC slab, wheel running test, strengthening, lifespan extension

1. INTRODUCTION

Deterioration of highway bridges due to traffic load is becoming a serious problem worldwide. Reinforced concrete (RC) slab is deemed one of the key members in road bridges such that serious damage of the slab will lead to the loss of function of the bridge and often results in the replacement of the whole structure [1].

Repair and strengthening by bonding fiber reinforced plastic sheet in grid pattern is developed to solve the problem of deteriorating bridge slabs. While carbon fiber sheets have shown promising strengthening effect when bonded to the tension side of slabs in grid pattern [2], there is still a lack of experimental data on how aramid fiber sheets (AFS) behave when bonded in the same manner and subjected to wheel traveling load. Therefore, in this research, wheel running fatigue tests were carried out for slab specimens bonded with AFS. The AFS used in this research has low fiber volume per unit area, thus result in considerably low tensile stiffness when arranged in grid pattern. The purpose is to examine the feasibility of AFS with low volume in strengthening highway bridge slabs. Performance of strengthening as well as fatigue lifespan extension compared to non-strengthened slabs is evaluated.

2. TEST PROGRAM

2.1 Specimens and Materials

2 identical RC slab specimens, namely slabs No.1 and No.2 were prepared. The specimens were designed in accordance with Specification for Design and Fabrication of Steel Highway Bridges, Japan Road Association, 1964. It is considered that bridges designed using the specification will be in need for strengthening in the near future, thus it is appropriate to investigate the strengthening effect of AFS on specimen with the similar design approach. The specimens were 3000mm long and 2000mm wide in longitudinal and transverse directions respectively with slab thickness of 160 mm and effective span of 1800 mm. Details of reinforcement are as shown in Fig. 1.

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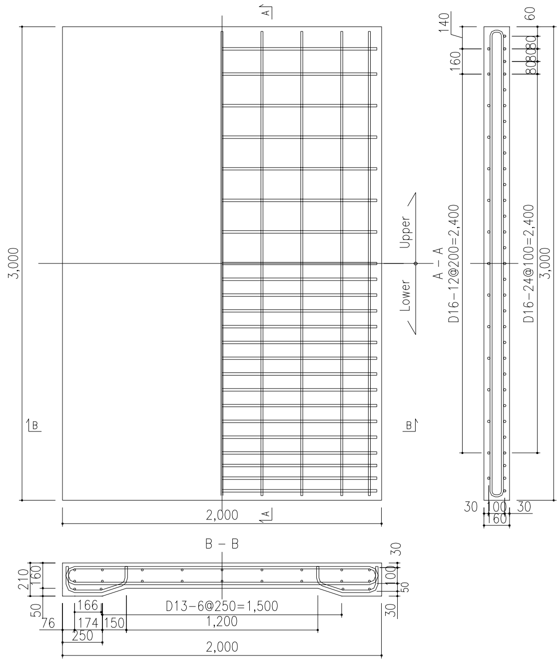


Fig. 1 Specimen details

Concrete was designed to attain a compressive strength of 28 N/mm^2 after 28 days from the day of casting. Table 1 presents the mechanical properties of concrete obtained from the cylinder tests during the course of fatigue tests.

Unidirectional AFS were used for strengthening in grid pattern as shown in Fig. 2. The width of each AFS is 250mm and the spacing between two sheets is 100mm. AFS were firstly bonded in transverse direction followed by longitudinal direction. Characteristics of the AFS are given in Table 2. The tensile stiffness of AFS is obtained by multiplying the design cross sectional area of AFS per its strengthening width of RC slab (in this case 350mm wide) by its Young's Modulus.

2.2 Loading Program

Fatigue tests by the wheel running machine of Osaka University were conducted. The loading position was fixed along the span center in longitudinal direction. Specimens were supported simply and elastically along the sides in longitudinal and transverse directions, respectively.

Prior to strengthening, slabs No.1 and No.2 were loaded with 60,000 strokes of wheel load of 120kN and 100kN, respectively. This is to induce preliminary damage as to simulate the actual deteriorating conditions of bridge slabs in service.

After strengthening, the fatigue tests were resumed with increase of wheel load magnitude in stages as presented in Fig. 3. Load was eventually maintained at maximum load of 170kN until the specimens failed.

Table 1 Properties of concrete

Specimen	No.1	No.2
Compressive Strength (N/mm^2)	47.0	43.4
Tensile Strength (N/mm^2)	2.6	2.6
Young's Modulus (kN/mm^2)	37.0	36.7

Table 2 Properties of AFS

Specimen	No.1	No.2
Tensile Strength (N/mm^2)	2060	2060
Young's Modulus (kN/mm^2)	118	118
Design Thickness (mm)	0.286	0.430
Tensile Stiffness (kN/mm)	24.1	36.2

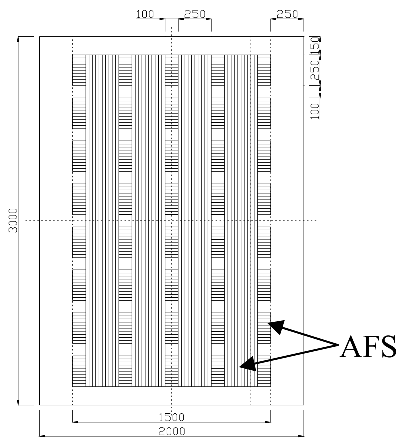


Fig. 2 Arrangement of AFS

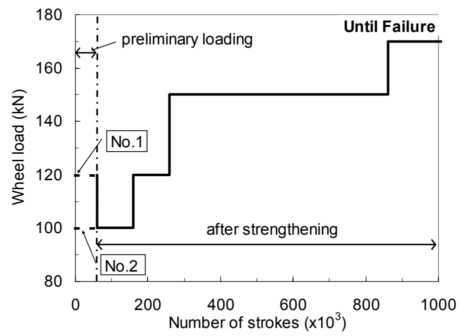


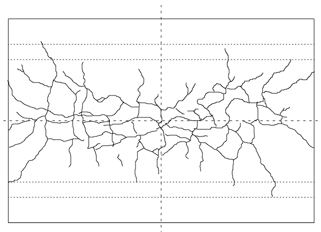
Fig. 3 Loading program

3. EXPERIMENTAL RESULTS

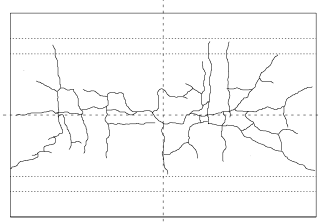
3.1 Fatigue Failure of Specimens

At the end of preliminary loading, cracks occurred on the bottom surface of the specimens as illustrated in Fig. 4. After strengthening and resumed with fatigue tests, both specimens were found to failed in punching shear, which is similar to the fatigue failure mode of normal RC slabs [1]. Total number of loading strokes counted from the start until the end of fatigue test when punching shear occurred for slabs No.1 and No.2 were 1,036,000 and 1,060,000, to the nearest 10^3 strokes, respectively. This means that after strengthening by AFS, the specimens sustained 976,000 and 1,000,000 strokes of wheel load respectively. Although No.2 was strengthened with AFS of tensile stiffness approximately 50% higher than that of No.1, the difference in total loading strokes between the specimens is too small. This could be due to high concrete properties of both specimens, as well as considerably low tensile stiffness of both AFS.

3.2 Deflection and Strain



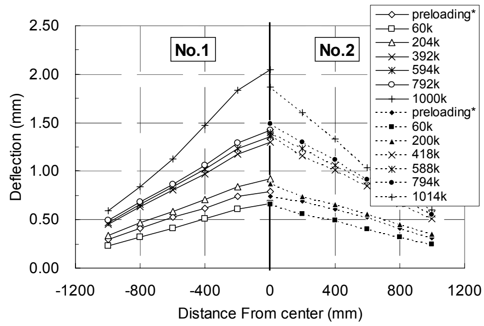
(a) No.1



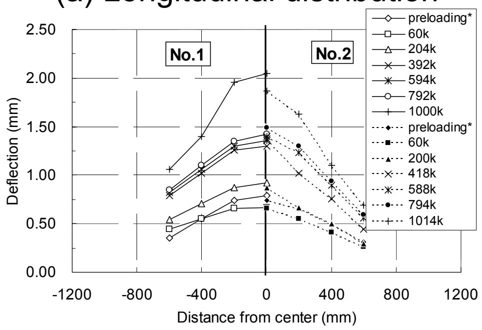
(b) No.2

Fig. 4 Cracks of specimens

Fig. 5 illustrates the variation of deflection at center span along longitudinal and transverse directions measured under static load equals to that of maximum wheel load in corresponding stages. For comparison purposes, Fig. 6 and Fig. 7 present the longitudinal distributions of transverse strains of tension reinforcements and AFS measured at 125mm from the longitudinal center of slab



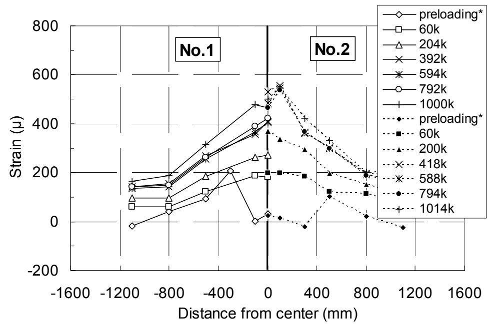
(a) Longitudinal distribution



(b) Transverse distribution

*end of preliminary loading

Fig. 5 Deflection



*end of preliminary loading

Fig. 6 Strains of main reinforcements in longitudinal distribution

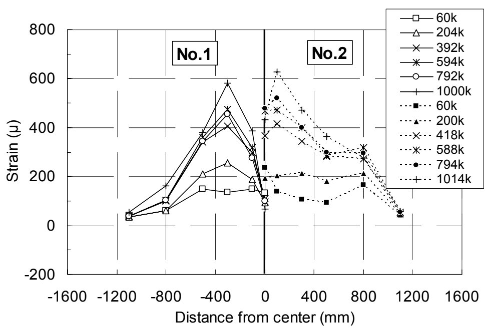


Fig. 7 Transverse strains of AFS in longitudinal distribution

under similar loading conditions as deflection measurements. It is found that deflections at 60,000 strokes, which were measured at the start of fatigue test after strengthening, were smaller than that at the end of preliminary loading. However, the strain of reinforcement as presented in Fig. 6 became higher after strengthening. This could be caused by redistribution of stress after strengthening. Further investigation is essential to clarify this. After strengthening, generally the deflections and strains of both specimens were very close to one another.

3.3 Deteriorating Process

Deterioration of the specimens throughout the fatigue tests can be expressed in terms of deterioration index, D_δ. D_δ is calculated with the following equation by considering the change in deflection at the center of slab:

$$D_\delta = \frac{(\delta - \delta_a)}{(\delta_c - \delta_a)} \quad (1)$$

where D_δ is the deterioration index, δ is the measured deflection at the center of slab, δ_a and δ_c are the theoretical deflections at the center of slab by considering whole concrete section effective and by neglecting tension side concrete, respectively.

Based on Fig. 8, it is found that immediately after strengthening with AFS, D_δ of both specimens were reduced significantly. D_δ of No.2 was higher than that of No.1 at the end of preloading. However, the rate became lower than that of No.1 due to better strengthening effect of AFS. Table 3 presents the decrease in center deflection as well as D_δ before and after strengthening.

During the middle stage of the fatigue tests, D_δ of No.2 exceeded that of No.1, with highest difference of 15% between the two specimens. Therefore it is suggested that concrete properties could be a more dominating factor than the properties of AFS for fatigue durability at the middle stage, in which concrete cracks propagated at a higher rate in No.2 compared to No.1. Although local sheet pulsating was observed along the cracks and possibly area adjacent to the cracks on the bottom surface of slab, the bond of AFS are still considered to be in sound condition because there was no delamination detected by knocking the sheet with a ball hammer to identify the peeling location.

Starting from approximately 900,000 strokes, D_δ of No.1 became greater than that of No.2. Both specimens marked significant increases in respective D_δ. The crack openings were considerably large and delamination of AFS has started to occur. The role of AFS in confining the opening of cracks became increasingly important. Eventually, No.2 which was strengthened with AFS of higher tensile stiffness sustained longer fatigue loading than that of No.1. Observations reveal that major delamination occurred at longitudinal cracks ± (300-400mm) away from the longitudinal center of slab, which developed as critical punching shear cracks.

Besides that, evaluation results also indicate that both the specimens failed shortly after D_δ reaches the value of 1.0, where the deflection of specimen was similar to the theoretical value of neglecting tension side concrete and is considered as the serviceability limit of the slab.

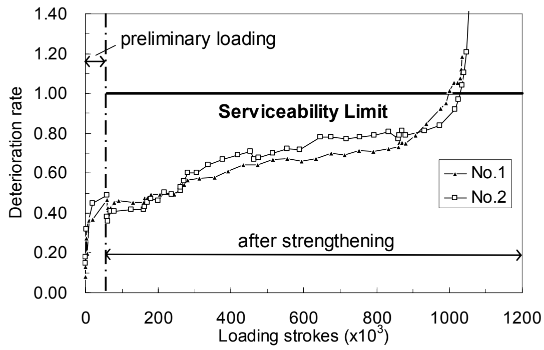


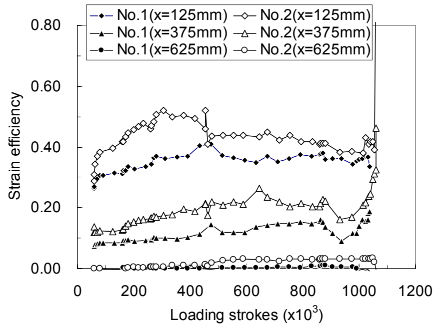
Fig. 8 Deteriorating process

Table 3 Decrease in δ and D_δ after strengthening

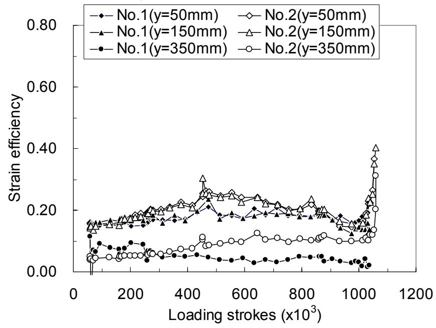
Specimen	No.1	No.2
Decrease in δ (%)	15.19	21.43
Decrease in D_δ (%)	18.09	22.00

3.4 Strain Efficiency

Strain efficiency of reinforcement, which is the ratio between measured strain at 100kN and analytical strain when allowable design stress is reached (=137N/mm^2), is used to investigate the effect of strengthening. By assuming the center of slab as the origin (0,0), with x-axis and y-axis lying along transverse and longitudinal directions respectively, examples of the strains efficiency of tension -side main and distributing reinforcements at

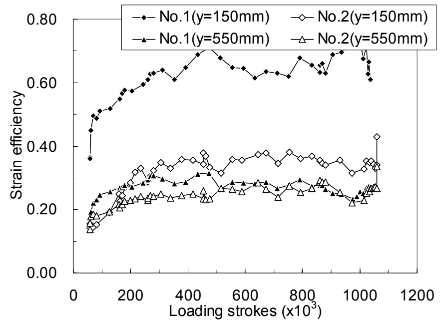


(a) Main reinforcement (y=0mm)

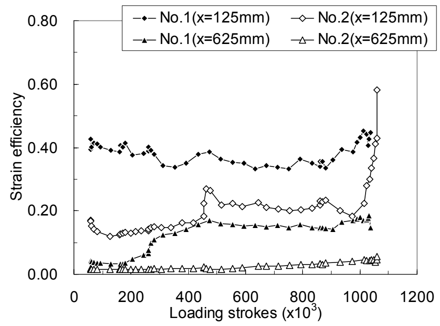


(b) Distributing reinforcement (x=0mm)

Fig. 9 Strain efficiency of reinforcements



(a) Main reinforcement direction (x=0mm)



(b) Distributing reinforcement direction (y=0mm)

Fig. 10 Strain efficiency of AFS

are shown in Fig. 9.

Strain efficiency for AFS is expressed as the ratio between measured strain at 100kN and analytical strain at allowable design stress for tension-side reinforcement by considering the proportional depth of the reinforcement and AFS from neutral axis of slab. Examples of strain efficiency of AFS are illustrated in Fig. 10.

Generally, the strain efficiency of tension-side reinforcement of No.1 is lower than that of No.2. The difference of strain efficiencies between the two specimens was particularly significant during the middle stage of the fatigue tests. This implies that higher stress was distributed to the reinforcements of No.2 compared to that of No.1. On the other hand, it is also noticed that the AFS strain of No.1 was higher compared to that of No.2, which contradicts with the results of strain of reinforcements. This could be attributed to the fact that precise assessment of strain development of AFS is very difficult because in wheel running fatigue test, concrete cracks propagated due to the complex combination of bending, shear and torsional moment. It was uncertain as how epoxy layer responded followed by local delamination and strain development of AFS under this combination of forces. Moreover, local delamination that occurred at locations of cracks all over the bottom surface of slab might hinder the precision of strain measurements on AFS.

4. FATIGUE LIFESPAN EXTENSION

In this study, strengthening of deteriorated slab specimens with AFS of low tensile stiffness has yielded encouraging fatigue durability with total wheel loading strokes of more than 1,000,000 strokes. Nevertheless, there is a need in examining the fatigue lifespan extension of the strengthened slabs compared to that of non-strengthened slabs. This would serve as useful information that contributes to developing a design method for strengthening of bridge slabs with AFS.

Although no experimental data of the lifespan was obtained for non-strengthened specimen, it is possible to calculate with the existing *S*-*N* curve expressed as in Equation (2), developed by taking into consideration the punching shear strength of normal RC slabs

[4]:

$$Log(\frac{P_o}{P_{sx}}) = -0.07856 LogN_{eq} + Log1.52 \quad (2)$$

where P_o and P_{sx} are the reference load and punching shear strength for fatigue failure of RC slabs respectively, and N_{eq} is the equivalent loading strokes under single reference load.

P_{sx} of specimens under non-strengthened condition is calculated with equation proposed by Matsui [4]. By assuming P_o=150kN, which is the average maximum wheel load measured in-situ for modern day traffic, N_{eq} for specimens under non-strengthened conditions can thus be obtained from Equation (2). On the other hand, based on Miner's rule and Equation (2), N_{eq} of specimens under AFS-strengthened condition is computed with the following equation:

$$N_{eq} = \sum (\frac{P_i}{P_o})^{12.76} * N_i \quad (3)$$

where P_i is the load during fatigue test and N_i is the total loading strokes that corresponds to P_i.

Fatigue lifespan extension ratio, α is obtained from the ratio between the N_{eq} of AFS-strengthened specimens and that under non-strengthened condition, and is presented in Table 4. No significant difference in α is found between the two specimens. This suggests that when AFS of considerably low tensile stiffness are used for strengthening RC bridge slabs, the fatigue durability of slabs does not differ significantly with the properties of AFS, especially when the slabs have good concrete properties.

5. CONCLUSIONS

Based on this study, the following conclusions can be drawn:

(1) Strengthening of RC bridge slabs with AFS of considerably low tensile stiffness in grid bonding pattern produces encouraging fatigue lifespan extension of 5.7~7.5 times that of non-strengthened slabs.

(2) The improvement in the deterioration of slabs as well as extension in fatigue lifespan is higher by strengthening with AFS of higher tensile stiffness. However, the difference in strengthening effect is not significant especially when the concrete properties are good and the properties of AFS used are considerably low.

Table 4 N_{eq} and α

Specimen	No.1	No.2
N_{eq} without strengthening (x10^3)	257	213
N_{eq} with strengthening (x10^3)	1476	1594
Lifespan extension, α	5.74	7.48

Since the deterioration of bridge slabs is not only caused by traffic load but also other factors which take place simultaneously, over-strengthening the slabs will be uneconomic. Hence, in certain circumstances, strengthening of RC bridge slabs with AFS of low tensile stiffness can be an excellent alternative to achieve cost-effectiveness.

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