# Fatigue Life Extension of Damaged RC Slabs by Strengthening with Carbon Fiber Sheets Attaching Method

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**Abstract**

A series of wheel trucking fatigue tests were conducted on the intentionally damaged reinforced concrete slabs of highway bridges strengthened with carbon fiber sheets attached by the grid bonding method. As a result of this experiment, it was found that grid-bonding method where carbon fiber sheets were bonded with intervals on the bottom surface of concrete decks was roughly 10 times higher than that of a non-strengthened RC slab, and there was no problem in adhesiveness in grid bonding parts.

## 1. Introduction[1)2)3)]

Recently, the deterioration of infrastructures becomes a very important social problem in Japan. Especially, the deterioration of bridges that are ones of structural factors for transportation network is recognized as the most important problem. The decks of road bridges are key members in bridges because many damage cases are found out in these members. The serious damages in decks lead to the loss of performance of bridges and it often becomes the cause of replacement of bridges.

To keep the performance of bridges, it is the one of most important propositions to keep the soundness of decks. In the situation as mentioned above, many methods of repair of decks are developed.

The carbon fiber sheets (hereafter called CFS) attaching method is the one of the remarkable repairing methods. Because it is able to apply to the bridge decks without any influence on the traffic and the application of this method is easier than other methods. However, it is often pointed out that there are following problems.

1. There is not any accurate checking method of the state of decks after application of the CFS attaching method.
2. In the decks applied with CFS attaching method, it is difficult to drain off the rainwater supplied from upside because of the lack of the performance on the draining water.

To solve these problems, the authors picked up the new attaching method. As shown in **figure 1**, the strips of CFS are attached in the grid style in this method. And the opening areas between CFS are used as the drainage for water and the windows for observation to check the situation of decks. In this method, the problems mentioned above will be solved.

But it is necessary to check the influence of the discrete arrangement of CFS because it is not clear whether the CFS in discrete arrangement is effective or not. Then the authors

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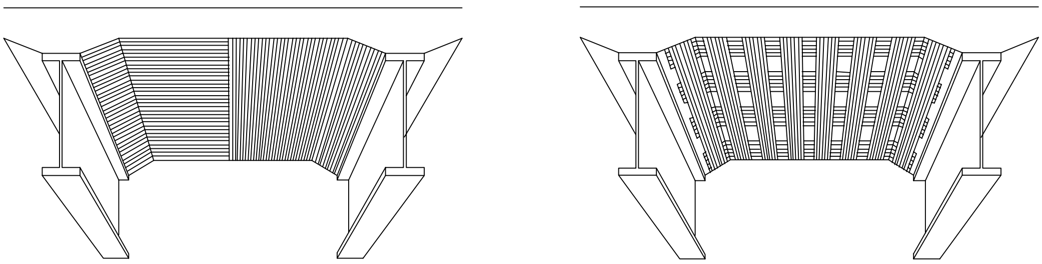
prepared the deck specimens applied the CFS attaching method in two arrangements and carried out the wheel load running test with these specimens to investigate the influences of arrangement of CFS.



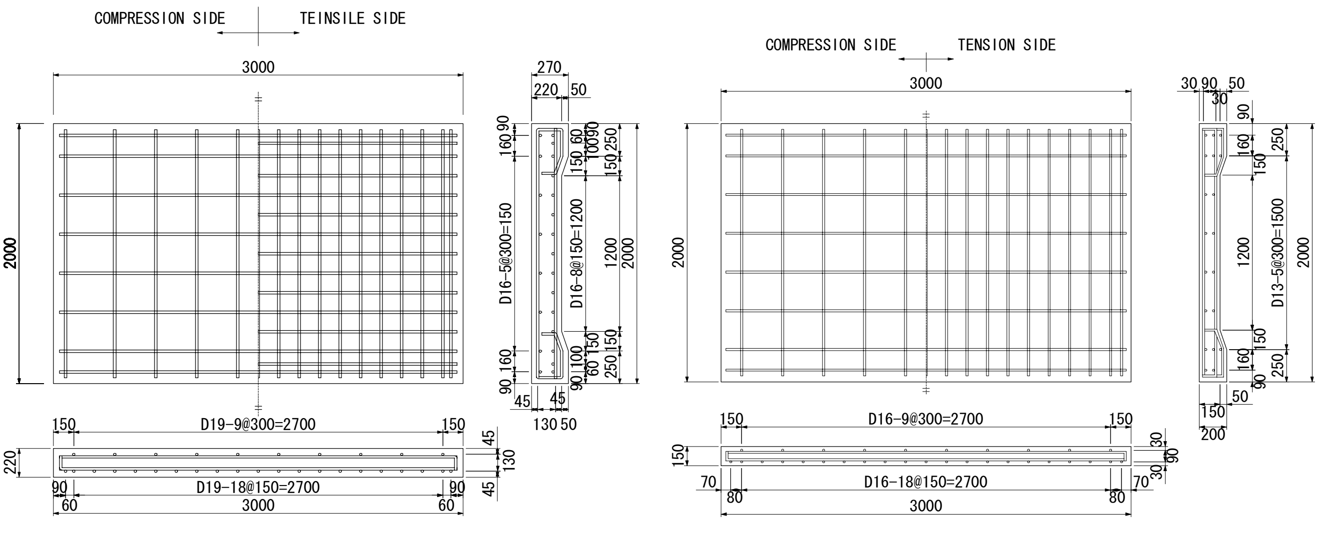
(a) Continuous arrangement (b) Grid arrangement

Figure 1 Arrangements of CFS

## 2. Structure of experiment

### 2-1 Test specimen

To investigate the influence of attaching styles, 6 specimens of decks were prepared. These specimens were divided into 3 groups (type A, B and C) by its structure. As an example, the structure of the specimens of type A and B used in this study is shown in **figure 2**. The dimensions of the specimens are 3,000mm long and 2,000mm wide. The thicknesses of specimens are 220mm (type A), 150mm (type B) and 180mm (type C). The span of the specimens is 1800mm long. The specimen of type A is designed with Japanese specifications for highway bridges in 1996. And the specimens of type B are also designed with Japanese specifications for highway bridges in 1964. The arrangements of reinforcements are shown in **table 1**.




(a) Type A (b) Type B

Figure 2 Structure of specimens

In this study, the authors picked up the two types of the arrangements of CFS to confirm the strengthening effect of new grid form arrangement. The tested arrangement is shown in **figure 3**. The width of CFS is 250mm and the spacing between CFS is set as 100mm or 150mm width as shown in figure 3. The elastic modulus of CFS used in this test is 440GPa. The attached values of CFS are set at 400g/m$^2$ (0.220mm) or 470g/m$^2$ (0.259mm) to check the influence of the attached value of carbon fiber. The combinations of the structure, types of carbon sheet and spacing between carbons sheets are shown in **table 2**.Properties of CFS are shown in **table 3**.

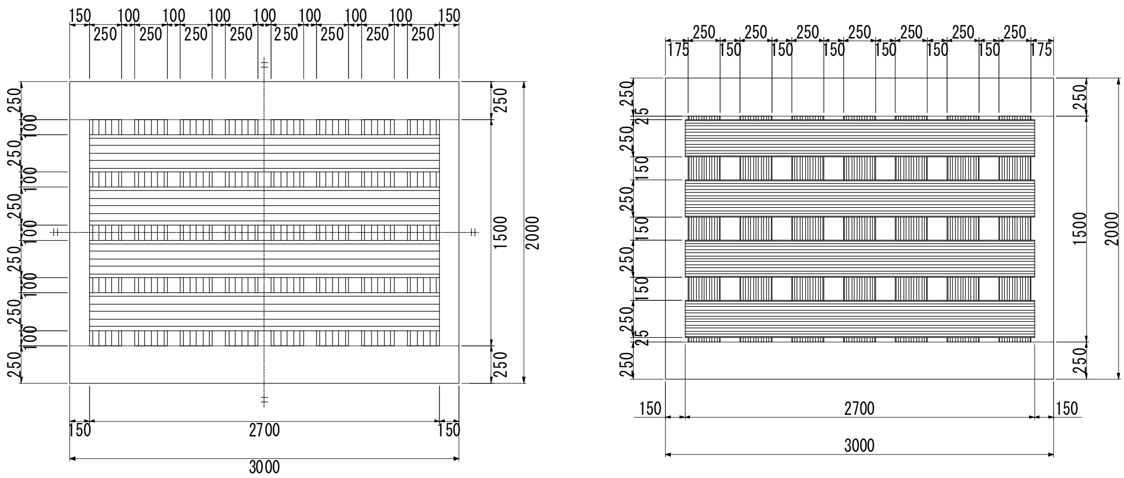
Table 1 Arrangements of reinforcements

| Thickness of specimens | Main bar | | Distribution bar | |
|---|---|---|---|---|
| | Diameter (mm) | Spacing (mm) | Diameter (mm) | Spacing (mm) |
| 220 mm | 16 | 150 (300) | 13 | 300 |
| 150 mm | 16 | 150 (300) | 13 | 140 (280) |
| 180 mm | 19 | 150 (300) | 16 | 150 (300) |

Notice) Parenthetical reference is the spacing in compression side

Table 2 Combination of parameters on tested specimens

| Specimen No. | Thickness of Slab (mm) | CFS(g/m$^2$) | Spacing (mm) | Remarks |
|---|---|---|---|---|
| 1 | 220 | - | - | Without strengthening |
| 2 | 150 | - | - | Without strengthening |
| 3 | 150 | 470 | 100 | |
| 4 | 150 | 400 | 100 | |
| 5 | 180 | 470 | 150 | |
| 6 | 180 | 400 | 150 | |




(a) Spacing: 100mm (a) Spacing: 150mm

Figure 3 Attachment styles of CFS

Table 3 Properties of CFS（standard value）

| | | |
|---|---|---|
| Fiber mass per unit area (g/m$^2$) | 400 | 470 |
| Tensile strength (N/mm$^2$) | 2400 | 2400 |
| Tensile elastic modulus (N/mm$^2$) | $4.40 \pm 0.44 \times 10^5$ | $4.40 \pm 0.44 \times 10^5$ |
| Design thickness (mm) | 0.217 | 0.255 |

**2-2 Loading method**

(1) Wheel trucking machine

The testing device is for simulating a wheel trucking machine acting directly on a deck slab. **Fig. 4** shows the outline of the testing machine. The testing machine is composed of the chassis running by applying load on the test specimen and the railway on which the chassis is reciprocated by motor rotation. **Table 4** shows the features of the testing machine.

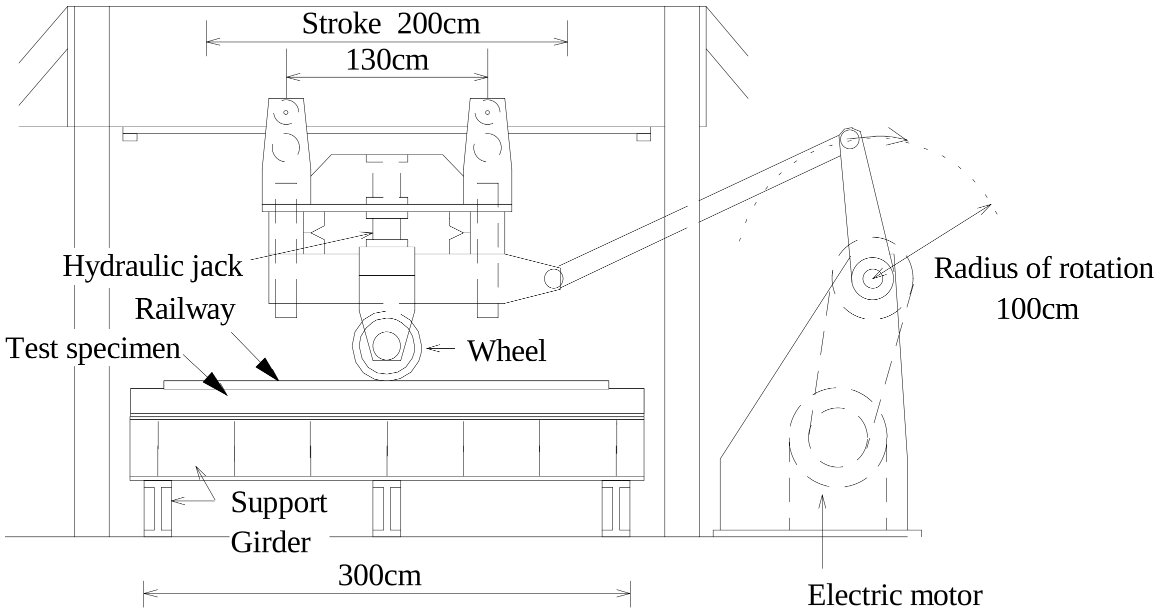



Fig. 4 Outline of testing machine

Table 4 Features of testing machine

| | |
|---|---|
| Loading capacity | 100 ～ 300 kN |
| Range of load trucking | ±100cm from the center of deck slab |
| Trucking speed | 112 m/min. ( 28 reciprocations / min. ) |
| Diameter and width of wheel | 50cm and 30cm |

(2) Method of supporting test specimen

The test specimen is supported so that two longer sides are supported simply and two other sides are supported elastically by transverse girders. Furthermore rising prevention device is mounted at four corners of deck slab to prevent the deck slab from rising on account of the wheel load-trucking test.

(3) Track

The track as shown in **Fig. 6** was adopted to realize the area load due to an actual tire running, because an iron wheel was used as the wheel of testing machine. To shift the load by ensuring a constant loading area, many blocks of same size were arranged on the top of deck slab and the traveling load was given to the deck slab through the blocks. The block size was of 12*30*5cm reduced to 60% of each side of the wheel loading area (50*20cm) required by the Road Bridge Regulation. Nineteen (19) blocks were arranged to get a caterpillar form having the clearance of 5mm among blocks. An iron plate of 10mm thick was placed on these blocks to keep the smoothness of wheel traveling surface and in addition, plywood was placed between deck slab and block, and between block and steel plate, respectively to relieve an impact and to prevent friction on the top of deck slab.

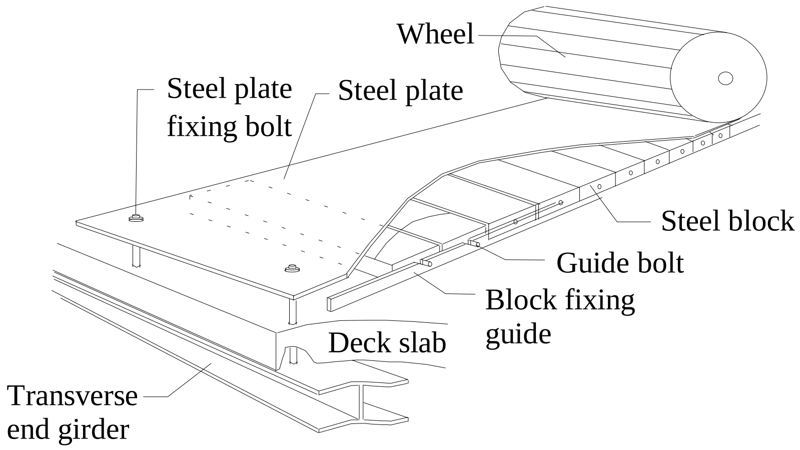



Fig. 6 Outline of track

**2-3 Loading procedures**

The specimens were pre-loaded by the wheel-trucking machine as the non-reinforcement condition, and after introducing crack damage, the specimens were reinforced with CFS. For No.3 - No.6 after pre-loading, CFS were bonded, and after reinforcing, these were set again to the wheel-trucking machine for the main loading test.

Generally, the fatigue durability (life of slab from the start of loading to failure) of non-strengthened RC slab is indicated uniformly by the relationship of applied load and number of cycles obtained by the existing studies (S-N curve). However, since the S-N curve for CFS strengthened RC slab has not been clarified yet, the fatigue durability shall be evaluated by relative comparison with non-strengthened specimens. Thus, in this test, as an evaluation of the reinforcing effect by CFS, the fatigue durability is evaluated by the relative comparison of the number of loading cycles until failure between non-strengthened and strengthened slabs.

In the experiments, the loads were increased stepwise. For the specimens No. 1, 5, and 6, loading program was started at 150kN and increased to 180kN and then to 210kN. For the specimens No.2-No.4 whose slab thickness are 15cm, loading program was started at

100kN and increased to 120kN, and then to 150kN, since 15cm thick slabs are much weaker than the slabs whose thickness is more than 18cm and damage proceeds rapidly and makes measurement difficult with the 150kN load (**see Figure 6**).

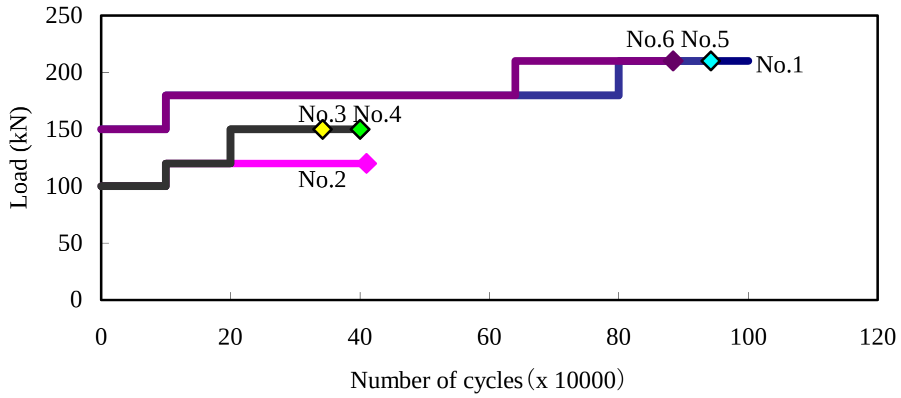



Figure 6 Loading procedures

**2-4 Calculation method of converted failure number of cycles**

As the applied loading programs are different among specimens, it is difficult to compare the fatigue durability directly with the number of cycles until failure. Thus, to examine the fatigue durability of specimens by comparison, the converted the number of cycles until failure at a constant loading with the reference load $P_0$=15tf was calculated using the S-N relationship Equation (1) of the WRM at Osaka University and the Miner's rule[4]. Here, for the shear strength of slab $P_{sx}$ [6], the value of the concrete slab without carbon fiber sheet was used.

$$Log\left(\frac{P_0}{P_{sx}}\right) = -0.7835Log(N) + Log(C) \tag{1}$$

Where, $P_0$: Reference load

$P_{sx}$: Punching shear strength of the effective cross section perpendicular to the main bars of the slab

N: Number of cycles until failure

C: Constant C= 1.52 when dried, C=1.24 when wet

Here, it is assumed that Miner's rule is applicable to the repeated loading under a random load condition. From Equations (1) and Miner's rule, for the RC slab subjected to random loading, the accumulated equivalent number of cycles $n_{eq}$ to the reference load $P_o$ is shown by Equation (2).

$$n_{eq} = \sum_{i=1,j}\left( n_i \cdot \left(\frac{P_i}{P_0}\right)^{\frac{1}{0.07835}} \right) = \sum_{i=1,j}\left( n_i \cdot \left(\frac{P_i}{P_0}\right)^{12.76} \right) \quad (2)$$

Where, $n_{eq}$: Equivalent number of cycles with reference load $P_o$
$n_i$ : Number of cycles with actual load $P_i$ in actual loading condition
$P_i$ : Actual load
$P_0$: Reference load

## 3. Experimental result and consideration

### 3-1 Converted number of cycles until failure

That cracks occurred in two directions was observed on the bottom surface, however, the specimen No.1 did not reach failure until the specified number of loading cycles. Then the test was finished after loading 1million cycles. Specimens No.2-No.6 failed with punching shear failure, which is the same failure mode of non-strengthened specimens. The relationship of the equivalent number of cycles until failure given by equation (2) and the non-dimensional index $P_o/P_{sx}$ is shown in **Table 5** and **Figure 7**. The S-N formula of the slab without CFS is shown with a solid line in Figure 7. The results of the fatigue test given by the wheel-trucking machine at Osaka University [7)] were also plotted.

Table 5 Converted the number of cycles until failure

| Specimen name | Punching shear capacity of slab $P_{sx}$(kN) | Reference load $P_0$(kN) | $P_0/P_{sx}$ | Experiment converted failure number of cycles $N_{eq}$ (cycles) | Remarks |
|---|---|---|---|---|---|
| No.1;t22-S96-Without strengthening | 41.0 | 15.0 | 0.366 | 21,911,657 | Finished before failure |
| No.2; t15-S64-Without strengthening | 21.6 | 15.0 | 0.693 | 18,546 | Punching shear failure |
| No.3;t15-S64-grid bonding EA80 | 21.5 | 15.0 | 0.699 | 148,366 | Punching shear failure |
| No.4;t15-S64-grid bonding EA68 | 21.3 | 15.0 | 0.706 | 242,366 | Punching shear failure |
| Calculation;t18-S68 -Without strengthening | 28.2 | 15.0 | 0.532 | 654,168 | Calculation result |
| No.5;t18-S68-grid bonding EA70 | 28.2 | 15.0 | 0.532 | 17,635,963 | Punching shear failure |
| No.6;t15-S68-grid bonding EA60 | 28.0 | 15.0 | 0.537 | 17,197,202 | Punching shear failure |

*t15-S64-grid bonding EA80:15cm thick slab, Designed by 1964 Specification for Steel Highway Bridges, Grid-bonding, reinforced with carbon fiber sheet which rigidity (EA) is 80 kN

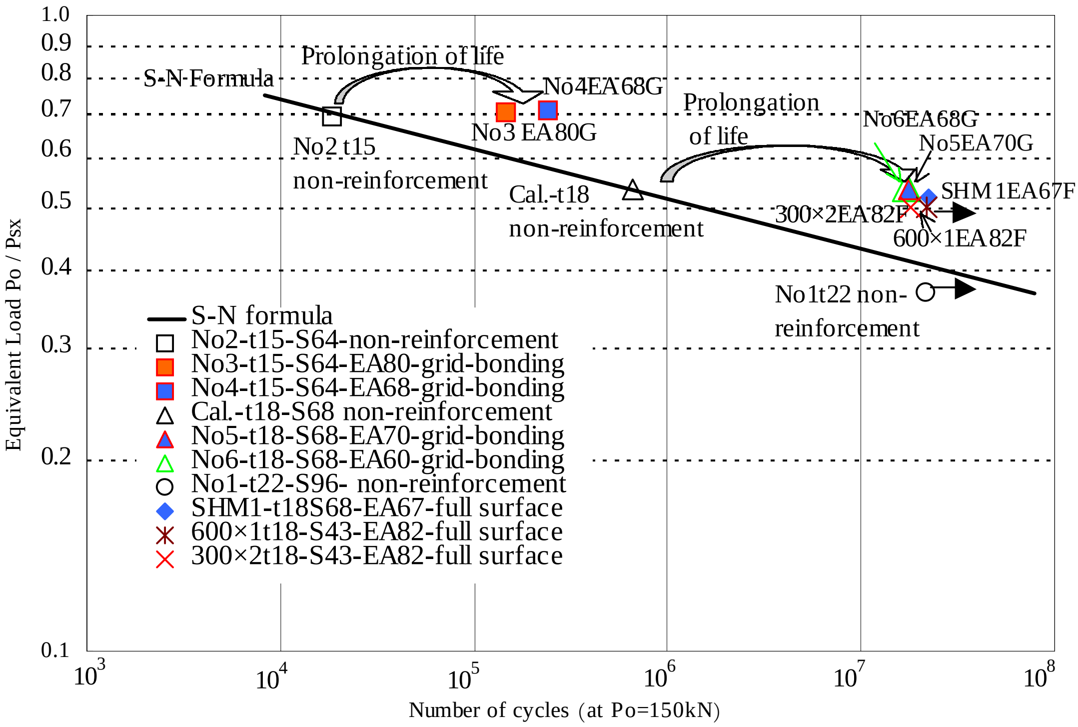
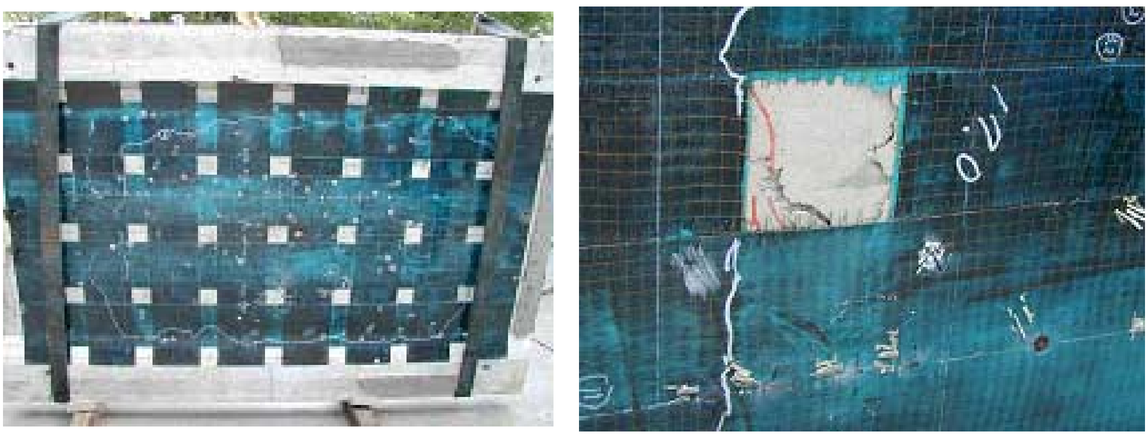



Figure 7 The relationship between number of cycles until failure and load $P_o/P_{sx}$

**3-2 Conditions of grid-bonded part and sheet overlap splices part**

During loading, there was no separation of CFS at crossing part (stepped parts) of the main bar and distribution bar directions. Grid bonding did not influence the shape of punching shear failure of slab concrete.

Moreover, even after the failure, there was no separation of the carbon fiber sheet observed in the main bar and distribution bar directions. There were neither new cracking and concrete separation along the edge of CFS, nor the damage of carbon fiber sheet at the grid step parts. In the overlap splice part (10cm), separation and damage of CFS did not occur. As the results, there was no problem in adhesiveness as well as in workability to the grid bonding (**see Photo 1**).



(a) Overview

(b) Enlargement of the grid part

Photo 1 Failure status of No.3

### 3-3 Considerations

With the objective of the more reliable maintenance for RC decks, a strengthening method using carbon fiber sheets was experimentally evaluated. The results of a series of wheel load running tests of the slabs strengthened by the grid bonding are summarized below:

(1) When 15cm thick RC slabs were strengthened with grid bonding carbon fiber sheets (No.3, No.4), fatigue durability was roughly 10 times higher than that of a non-strengthening RC slab (No.2) and came to have sufficient fatigue durability for practical use.

(2) When the 15cm thick slabs were strengthened with grid bonding with 2 types of intermediate modulus of elasticity CFS (No.3 with fiber mass per unit area of 400g/m$^2$, No.4 with Fiber mass per unit area of 470g/m$^2$), there was no significant difference in fatigue durability between the 2 types, and strengthening with even 400g/m$^2$ CFS has significant fatigue durability. In this case, the tensile rigidity of CFS is 68kN/mm, which is about 17% less than the current 82kN/mm.

(3) When 18cm thick slabs (No.5, No.6) strengthened with grid bonding CFS, the slabs came to have sufficient fatigue durability, about 20 times compared to the calculation value obtained by the S-N relationship of non-strengthened RC slabs.

(4) When the 18cm thick slabs were strengthened with grid bonding with 2types of intermediate modulus of elasticity CFS (No.5 with fiber mass per unit area of 400g/m$^2$, No.6 with fiber mass per unit area of 470g/m$^2$), there was no significant difference in fatigue durability between the 2 types, and strengthening with even 400g/m$^2$ CFS has significant fatigue durability. In this case, the tensile rigidity of CFS is 60kN/mm, which is about 25% less than the current 82kN/mm.

(5) When the test result (No.5, No.6) of grid-bond strengthened 18cm thick slabs in this experiment were compared with the previous result (SHM1) of full-surface bonding of CFS, there was no significant difference. Therefore, the grid bonding method had equivalent strengthening effect to the full-surface bonding.
When the amount of strengthening was about the same, grid bonding and full-surface bonding were shown to obtain equivalent reinforcement effects.

(6) For economy, grid bonding reduces the amount of strengthening members as well as bonding areas. In terms of direct work cost, including material costs and construction costs (surface treatment, level adjustment, bonding, and finishing), a reduction of about 15% (in case of 15-17cm thick slabs) or about 20% (in case of 18-20cm thick slabs) is possible compared to the current full-surface bonding of intermediate modulus of elasticity CFS (EA=82kN/mm).

## 4. Conclusion

Conclusions obtained in this study are as follows:

1. RC slabs were strengthened with grid bonding CFS came to have sufficient fatigue durability for practical use.
2. Grid bonding specimens were observed in the shape of punching shear failure of slab concrete as well as the full-surface bonding.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