ORAL/POSTER REFERENCE:ICF100819OR

# EXPERIMENTAL AND ANALYTICAL STUDIES ON PEELING BEHAVIOR AND SPALLING RESISTANCE EFFECT OF CFS BONDED TO CONCRETE

Zhishen WU[1], Toshihiro ASAKURA[2], Hiroyuki YOSHIZAWA[3], Hong YUAN [4], Akira KOBAYASHI[5], and Toru TAKAHASHI[6]

[1] Department of Urban & Civil Engineering Ibaraki University, Hitachi city, 316-8511,Japan
[2,4]Department of Earth Resources Engineering Kyoto University, Kyoto city, 606-8501, Japan
[3,5] Nippon Steel Composite Co., Ltd., 3-8 Nihonbashikobuna-cho Chuo-ku, 103-0024,Tokyo, Japan
[6]Sho-Bond Corporation, 3-18 Kandanishiki-cho, chiyoda-ku, 101-8468, Tokyo, Japan

## ABSTRACT

In this paper, the peeling behavior and the spalling resistance effect of externally bonded continuous fiber sheets (CFS) were firstly investigated experimentally through a series of punching shear tests. CFS applied concrete slabs with a hole in center were used for the test specimens. Specimens were varied in bonding length of CFS, diameters of spalling columnar concrete (indenter), types of fiber that were composed of CFS. Secondly, a fracture energy method was proposed for modeling the membrane peeling behavior and for evaluating spalling resistance effect of externally bonded CFS. It is realized that only one material parameter, interfacial fracture energy of CFS-concrete interface ($G_c$), was necessary to represent the interfacial behavior. Finally, the close agreement between the predicted results from the proposed analytical method and the experimental results was demonstrated by means of some numerical examples.

## KEYWORDS

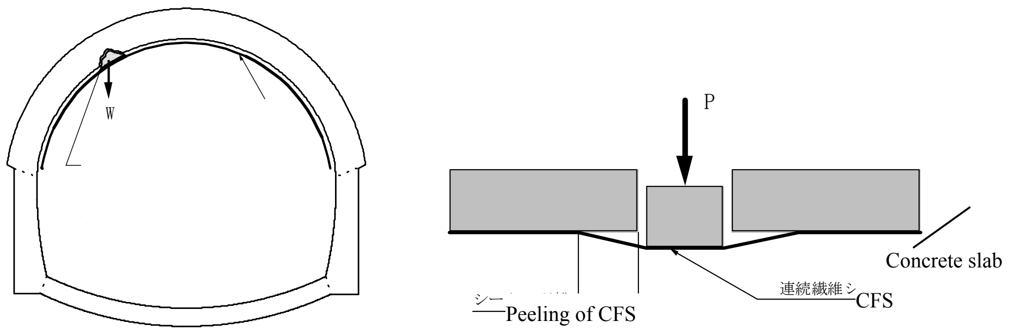
Continuous fiber sheet, Fracture energy, Peeling, Spalling resistance

## 1. INTRODUCTION

Today many of the existing tunnels need counter measures to prevent the peeling and spalling of their lining concrete caused by the action of ground pressure, the deterioration of concrete materials, etc. There are also road bridges and railway bridges which require counter measures to prevent the peeling and spalling of pieces of their concrete caused by the deterioration of concrete, the corrosion of steel reinforcement, etc.

In recent years, continuous fiber sheet (CFS) has been increasingly used to reinforce or repair tunnel linings and the slabs of viaducts. When CFS is applied to a concrete lining slab to prevent pieces of the concrete from peeling and spalling, not only the in-plan shear stress but also the out-of-plane shear stress that makes the CFS peel off from the concrete surface are imposed on the interfacial crack tip between the CFS and the surface of concrete. In this case, the fracture mode in which a interfacial crack develops is considered to be a combination of the crack development of both Mode I and Mode II in terms of fracture mechanics.

We think that the fracture mechanism of peeling of CFS under the in-plane shear stress is different from the mechanism of that under the combination of in-plane and out-of-plane shear stress. Therefore, assuming that a piece of concrete spalls from the surface of concrete lining, we carried out a punching shear test of concrete slabs of which CFS bonded to the bottom surface. In the experiments, the bonding length of CFS, the diameter of concrete indenter were the experimental parameters[1)]. As a result, we proposed a new analytical technique using interfacial fracture energy, $G_c$, and compared the experimental results with the analytical results obtained using the new technique.




(a) Schematic diagram of spalling of concrete piece from concrete lining (b) Schematic diagram of present test

**Figure 1**: Schematic diagram of spalling of concrete piece and present test

## 2. SCHEME OF EXPERIMENT

### 2.1. Experimental apparatus

The experiments were carried out using a static load tester and concrete slab (W230 x L230 x H20 cm) provided with a hole in the center. CFS was bonded in two orthogonal layers (0/90) to the lower surface of the slab, and an indenter made of concrete was fitted in the hole. The CFS was bonded to the lower surface of the concrete slab and the indenter. The experiments were conducted under controlled displacement conditions. The load was applied to coerce the indenter into moving to force the CFS to peel off from the slab. In this way, CFS applied concrete slabs were subjected to a punching shear test in which a forced displacement was given to the indenter to peel the CFS off the concrete slab. The compression strength of the concrete used for the slabs was 28 $N/mm^2$. Displacement was measured at three points as shown in Figure 2. Mechanical properties of CFS using in this test are shown in Table 1.

### 2.2. Experimental cases

In the experiments, seven different cases were tested. Standard case (No. 1) is as follows. Hole diameter is 200 mm, Type of CFS is high strength carbon fiber. Bonding length is 500mm.

As the experimental parameters, fiber types, hole diameter, and bonding length are varied. The detail conditions are shown in Table 2 and Figure3.

Each specimen was subjected to surface preparation, coated with primer, and smoothed with epoxy putty before the CFS was bonded to it with epoxy resin. For specimen No. 3 with constraining plates, 4 steel plates, size of W50 x L600 x t3.2 mm, were arranged in a square at a distance of 30 cm from the hole center. Each of the plates was fixed with three M10 anchor bolts at a 250 mm pitch.

### 2.3. Experimental procedure

The test apparatus was controlled based on displacement and loading was conducted step-wisely. The loading speed was 1 mm/min and the pushdown rate was 0.5 mm per step. In consideration of the stress relaxation right after the loading, the displacement and the load were measured two minutes after the loading.

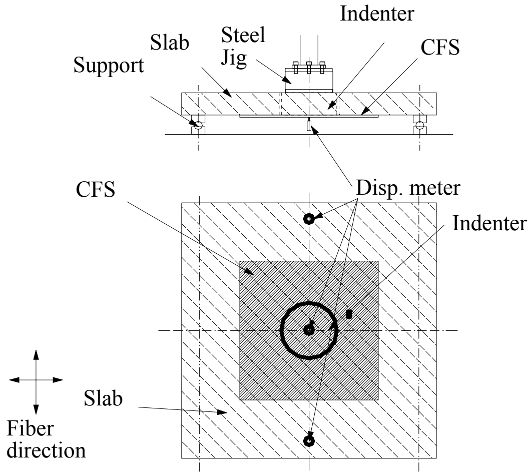



**Figure 2:** Experimental apparatus and specimen shape

**TABLE 1**
CHARACTERISTICS OF CFS

| CFS type | Fiber areal weight $g/m^2$ | Young's modulus E GPa | Tensile strength MPa | Design thickness t mm | Stiffness of CFS sheet E・t $*10^6$ N/mm |
|---|---|---|---|---|---|
| High-strength Carbon Fiber | 200 | 235 | 4,150 | 0.111 | 26.1 |
| Aramid Fiber | 280 | 118 | 2,450 | 0.193 | 22.8 |
| Glass Fiber | 300 | 74 | 1,650 | 0.118 | 8.7 |

**TABLE 2**
EXPERIMNETAL PARAMETERS

| NO. | Hole diameter mm | CFS type | Bonding length mm | Fiber areal weight $g/m^2$ | Remarks |
|---|---|---|---|---|---|
| 1 | ϕ 200 | High-strength Carbon Fiber | 500 | 200 | Standard |
| 2 | ϕ 200 | High-strength Carbon Fiber | 900 | 200 | Bonding length |
| 3 | ϕ 200 | High-strength Carbon Fiber | 500 | 200 | Constrained with plates |
| 4 | ϕ 500 | High-strength Carbon Fiber | 500 | 200 | Hole diameter |
| 5 | ϕ 1000 | High-strength Carbon Fiber | 400 | 200 | Hole diameter |
| 6 | ϕ 200 | Aramid Fiber | 500 | 280 | Aramid Fiber |
| 7 | ϕ 200 | Glass Fiber | 500 | 300 | Glass Fiber |

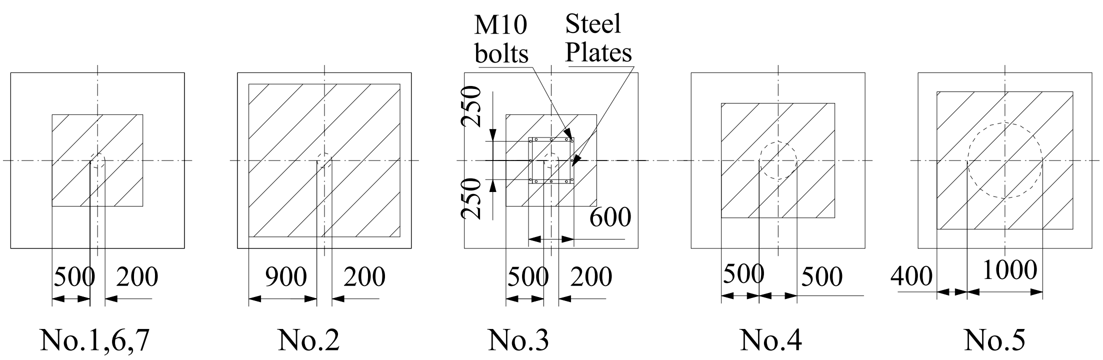



**Figure 3:** Scheme of specimens

## 3. EXPERIMENTAL RESULTS

Figure 4 shows the load-displacement curves obtained by the punching shear test. Here, the load values are those two minutes after load application. Photo.1 shows an example of expansion of the peeling zone of CFS. The white lines indicate the peeling zones of CFS when the indenter displacement was increased in increments of approximately 2 mm.

Table 3 shows the maximum load ( load value measured two minutes after load application) for each of the specimens.

With the exception of the specimen bonded with glass fiber sheet (No.7), all the specimens showed maximum load right before the CFS peeled off completely (the CFS did not rupture at all).

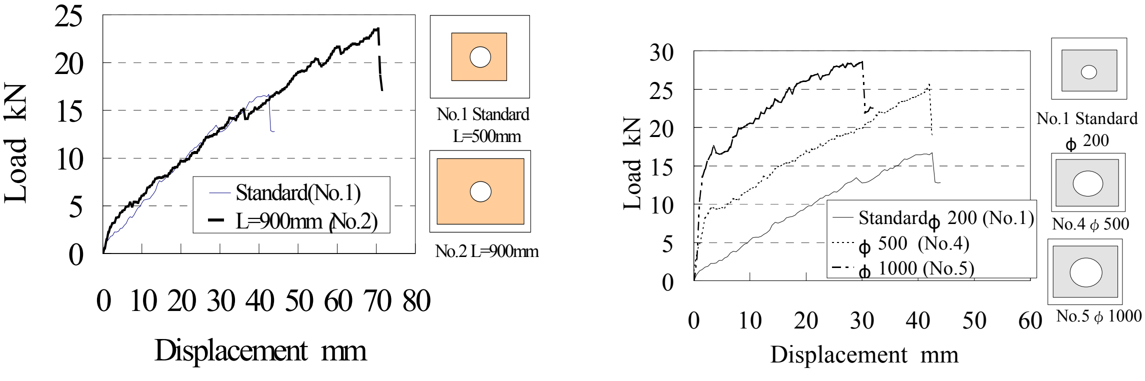
In the early stages of peeling, the shape of peeling zone was circular. As the CFS continued peeling, the peeling zone became squarely shape because the continuous fibers were aligned diagonal orientations. In case of No.7 (glass fiber specimen), the sheets were ruptured at the edge of the concrete indenter right before they peeled off completely.

**TABLE 3**

EXPERIMENTAL RESULTS

| NO. | Hole diameter mm | CFS type | Bonding length mm | Max. displacement mm | Max. load kN | Failure criteria |
|---|---|---|---|---|---|---|
| 1 | ϕ 200 | High-strength Carbon Fiber | 500 | 43.0 | 17.0 | Debonding failure |
| 2 | ϕ 200 | High-strength Carbon Fiber | 900 | 71.0 | 23.9 | Debonding failure |
| 3 | ϕ 200 | High-strength Carbon Fiber | 500 | 46.0 | 33.7 | Bolt pull out Debonding failure |
| 4 | ϕ 500 | High-strength Carbon Fiber | 500 | 42.5 | 26.1 | Debonding failure |
| 5 | ϕ 1000 | High-strength Carbon Fiber | 400 | 32.0 | 29.1 | Debonding failure |
| 6 | ϕ 200 | Aramid Fiber | 500 | 48.0 | 24.6 | Debonding failure |
| 7 | ϕ 200 | Glass Fiber | 500 | 48.0 | 16.4 | Sheet rupture |


**Photo.1** Progress of peeling off zone (No. 2)




(a) effect of bonding length (b) effect of hole size

**Figure 4:** Load-displacement curves

**a) Effect of sheet bonding length**

As shown in Figure 4(a), with a given hole diameter, the maximum load increased as the sheet bonding length was increased. However, it was confirmed that the gradient of the load-displacement curve remained almost the same even when the sheet bonding length was changed.

**b) Effect of hole diameter**

As shown in Figure 4(b), the larger the hole diameter, the larger was the starting load (about 1 kN for No.1, about 9 kN for No.4, about 17 kN for No.5). However, even when the hole diameter was changed, the gradient of the load-displacement curve remained almost the same. As shown in Figure 5, the relationship between indenter vertical displacement and sheet peeling length is almost linear. With a given amount of vertical displacement of the concrete indenter, the larger the hole diameter, the greater is the sum of the sheet peeling length and the hole radius. Because of this, the larger the hole diameter, the higher was the maximum load of punching shear at a given amount of indenter vertical displacement.

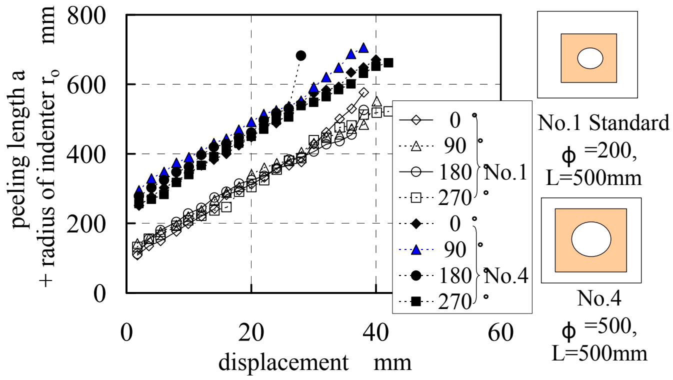



**Figure 5:**Relationship between peeling length and indenter vertical displacement (No.1,4)

## 4.COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL RESULTS

### 4.1 Analytical technique

Figure 6 shows the equilibrium of forces between vertical load P applied to the indenter and tensile force of the CFS. In this figure, α, a, $r_o$, and L represent peeling angle in fiber orientation, sheet peeling length, indenter radius, and sheet bonding length respectively. Analyses were conducted on the assumption that when the sheet is bonded in two layers, one orthogonal to the other, the peeling zone becomes square in form when the steady state is reached. Using Young's modulus of CFS E, CFS thickness t, indenter radius $r_o$, sheet peeling length a, and indenter vertical displacement u, load applied to the indenter P, can be expressed as follows [2)].

$$P = 4 \cdot E \cdot t \cdot (r_0 + a) \cdot \beta \cdot \left(1 - \frac{1}{\sqrt{1+\beta^2}}\right), \quad \beta = \frac{u}{a} = \tan\alpha \tag{1}$$

Fracture energy, G, can be obtained by the following equation.

$$G = E \cdot t \cdot \left(\frac{1}{2} \cdot \beta^2 + \frac{1}{\sqrt{1+\beta^2}} - 1\right) - E \cdot t \cdot \frac{a}{a + r_0} \cdot \left(\frac{1}{2} \cdot \beta^2 - \sqrt{1+\beta^2} + 1\right) \tag{2}$$

When the sheet peeling length is sufficiently greater than the indenter radius, fracture energy, G, can be expressed as follows.

$$G = E \cdot t \cdot \left(\sqrt{1+\beta^2} + \frac{1}{\sqrt{1+\beta^2}} - 2\right) \tag{3}$$

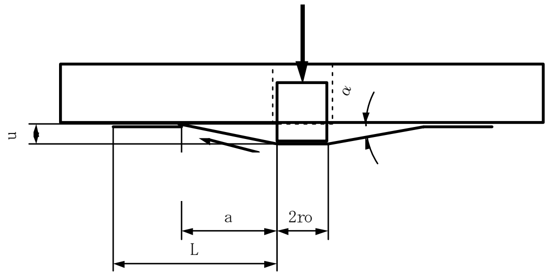



**Figure 6:**Equilibrium of forces between CFS and cylinder

### 4.2 Comparison between analytical results and experimental results

Table 4 shows the comparison between the analytical results and experimental results obtained with large specimens at $G_c$ = 0.4 kN. In the analysis, it was assumed that the maximum load and the maximum displacement were reached when the sheet peeled off completely. In terms of both the maximum load and maximum displacement, the analysis values agree well with the experimental values.

**TABLE 4**

COMPARISON BETWEEN EXPERIMENTAL AND ANALYSIS VALUES ($G_c$ = 0.4 kN/m)

| Specimen No. | Analysis | | Experimental | | Experimental /Analysis | |
|---|---|---|---|---|---|---|
| | Max. Load kN | Max. disp. mm | Max. Load kN | Max. disp. mm | Max. Load kN | Max. disp. mm |
| L-1 | 20.0 | 43.5 | 17.0 | 43 | 0.85 | 0.99 |
| L-2 | 34.2 | 78.8 | 23.9 | 71 | 0.70 | 0.90 |
| L-4 | 23.7 | 42.6 | 26.1 | 43 | 1.10 | 1.01 |
| L-5 | 26.5 | 33.3 | 29.1 | 32 | 1.10 | 0.96 |
| L-6 | 21.9 | 44.8 | 24.6 | 48 | 1.12 | 1.07 |
| L-7 | 15.2 | 57.4 | 16.4 | 48 | 1.08 | 0.84 |

## 4. CONCLUSIONS

In order to confirm the effect of CFS bonded to the surface of concrete to the prevention of concrete pieces from spalling from a concrete structure, we carried out a series of punching shear test experiments. In the experiments, the parameters such as CFS type, diameter of a cylinder simulating concrete piece which spalls, and bonding length of CFS were varied. And a new analytical technique that uses the interfacial fracture energy $G_c$ was proposed. By comparing the analysis results with the experimental results, we could obtain the following conclusions.

1) When a CFS is bonded in two layers, one orthogonal to the other, the load of punching shear is almost proportional to the displacement of the concrete indenter or the peeling length of the CFS.
2) By applying our new analytical technique that uses interfacial fracture energy $G_c$ between CFS and concrete (when the sheet is bonded in two layers, one orthogonal to the other), it is possible to accurately calculate the maximum load, maximum displacement, merely by determining the value of $G_c$ experimentally.

## REFERENCES


1) Asakura,S., Kojima,Y., Takahashi,T., Yoshizawa,H.: Experimental study on effect of continuous fiber sheet to prevent spalling of tunnel lining concrete, First-Australasian Conference on Composite Materials (ACCM-1), pp.106-1-106-4,1998 .
2) Wu,Z., Asakura,S., Yoshizawa,H., Yuan,.H., Kobayashi,A., and Takahashi,T.: Experimental and analytical studies on peeling behavior and spalling resistance effect of externally bonded continuous fiber sheets. J. Materials, Conc. Struct., Pavements, JSCE, No.662/V-49,pp.45-58, 2000.11.