# SPRAYED-UP FRP STRENGTHENING FOR CONCRETE STRUCTURES

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## ABSTRACT

A new repair and strengthening method by spraying carbon or glass chopped fiber with vinyl ester resin upon concrete structures is introduced. This paper reported the outline of this new strengthening method and the results of experimental programs for RC columns and bond / anchor test between FRP and concrete. This method is engineered systemically for the purpose of repair and strengthening of concrete structures using sprayed-up FRP composites. Carbon or glass fiber chopped with 1.5 or 2 inch-length is sprayed with vinyl ester resin using the air-compressed spray machine on the surface of concrete structures directly. The anti-symmetrical loading test of rectangular columns was carried out for the purpose of confirming fundamental behaviors of RC structures strengthened by sprayed-up FRP system. As the result, it can be recognized that the similar shear reinforcing effect is obtained in either way spraying or fiber sheet. Anchor method by the advantage of sprayed FRP’s flexibility is investigated. Anchor bolts or slits are set on the concrete surface, FRP sprayed in and on them. Compared with fiber sheet, the bond strength by sprayed FRP has over the equivalent of one by sheet, when the thickness is set having equal rigidity. By filling the FRP to the slit, the mechanical bearing can be expected.

## KEYWORDS

FRP, spray up, carbon fiber, glass fiber, vinyl ester, column, bond, anchor, slit

## INTRODUCTION

Nowadays, strengthening by post casting concrete, steel plate jacketing, fiber reinforcements such as carbon, aramid, and glass are utilized as seismic strengthening methods for concrete structures. Recently, a seismic strengthening method by wrapping continuous fiber sheets has often been used, since the constructibility and durability is superior. However, materials using continuous fibers are expensive. On the spread of seismic strengthening for buildings and infrastructures in future, simple methods of strengthening with low cost should not only be suggested, but also seismic behaviors should be cleared.

In this study, a new, inexpensive, and simple strengthening method for concrete structures is discussed and suggested in order to improve future seismic strengthening. This method using short fibers with vinyl ester is a new combination of materials as seismic strengthening. Chopped short fibers of carbon and glass with vinyl ester resin are sprayed in place on the concrete structures. It is called “Sprayed-Up FRP (Fiber Reinforced Polymer).” Benefits of using vinyl ester resin in this strengthening method are that it takes shorter time to harden the resin than epoxy resin. In addition, the mechanical properties of vinyl ester resin are the same as the one of epoxy resin.

In this paper, the outlines of this method and the results of column test under the anti-symmetrical loading are reported. In addition, the bond behavior between FRP and concrete, and anchoring behavior using slit (groove) are reported.

## OUTLINE OF SPRAYED-UP FRP STRENGTHENING METHOD

Figure 1 illustrates the idea of the sprayed-up FRP strengthening method for reinforced concrete buildings. Photo 1 and 2 show the construction site of sprayed column specimens. In this method, resin is carried through a narrow hose by an air compressor. The resin is mixed with short fibers such as carbon or glass at a tip of the narrow hose. The mixed materials are sprayed directly on a surface to be reinforced. After that, the surface is made flat by a roller. The resin will be hardened and the whole sprayed structure will be reinforced with FRP. This method makes seismic strengthening possible that all structure members, which are columns, beams, walls, and slabs, are monolithic since it is possible to reinforce an entire interior structures in building structures.

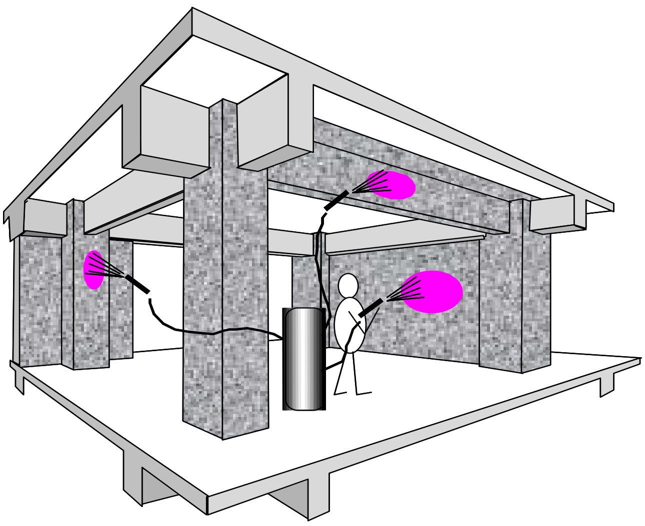

Figure 1: Sprayed-up FRP strengthening

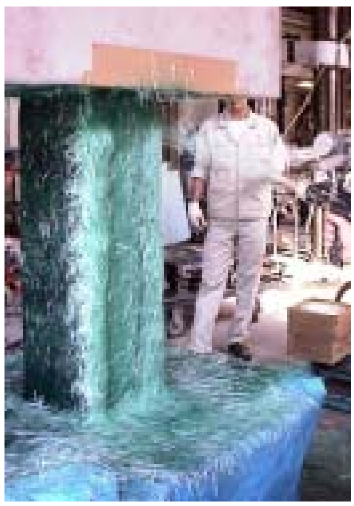

Photo 1: Sprayed fiber

Photo 2: Surface curing

The installing procedure of the sprayed-up strengthening is as follows;

Step 1. Base arrangement; Surface of concrete is polished by a disc-sander and cleaned by air.

Step 2. Primer resin coating; Primer resin is applied to the surface in order to make highly adhesive between concrete and putty/resin.

Step 3. Putty arrangement; Dent areas and steps on concrete surface are filled with putty and make the surface flat in order to prevent from partial stresses of FRP and air voids on concrete. After putty dried, the surface is sanded.

Step 4. Resin coat; In order to make fibers more adhesive, resin is coated first by a spray gun.

Step 5. Spraying (Photo 1); Resin and short fiber are sprayed on concrete at a same time by a spray gun. The lengths of the carbon fiber and glass fiber are 2.0 inches and 1.5 inches, respectively.

Step 6. Impregnation (Photo 2); Entrapped air is rolled out.

In this study, in order to compare structural behaviors of sprayed-up FRP to the ones of continuous fiber sheet strengthening, preliminary arrangements as Step 1 through 3 are done. However, it is a goal to obtain sufficient seismic behaviors by taking only after Step 4.

## MECHANICAL PROPERTIES OF SPRAYED-UP FRP

A total of sixty coupon specimens of each sprayed-up FRP were prepared as Type A (JIS K7054) test pieces. Thirty specimens were made with carbon fiber (CF-SU), and the other thirty specimens for glass fiber (GF-SU). Based on a tensile test method for plastics reinforced by glass fiber (JIS K7054), a tensile test was carried out for these Type A test pieces. In order to compare the differences of characteristics between sprayed-up FRP and fiber sheets, another sixty Type B (JIS K7054) test pieces were also prepared and tested in the same tensile test. Thirty of them were made by carbon fiber sheet (300g/m$^2$) with one layer (CF-HU). The other thirty were made by glass fiber sheet (444g/m$^2$) with 4 layers (GF-HU). The specified thickness of sprayed-up FRP for CF-SU and GF-SU is 3.0mm and 4.5mm, respectively.

Table 1 and Figure 2 show the tensile test results and the typical stress-strain diagram ($\sigma$-$\varepsilon$), respectively. The measured sectional areas including resin are applied, and elastic modulus is a secant stiffness of the 10%-50% tensile strength. The tensile strength of CF-SU is about one tenth of the one of CF-HU. GF-SU is about one fifth of GF-HU. The tensile strength of CF-SU is approximately the same as the one of GF-SU. Regarding elastic modulus, CF-SU is about one forth of CF-HU. GF-SU is also about one forth of GF-HU. The elastic modulus of CF-SU is approximately twice as large as the one of GF-SU. From these results, the thickness of sprayed-up CFRP needs to be about 6.5mm in order to expect the similar strength of specimens with one layer of carbon sheet (300g/m$^2$). As shown in Figure 2, $\sigma$-$\varepsilon$ relationships for sprayed-up FRP is not perfect linear.

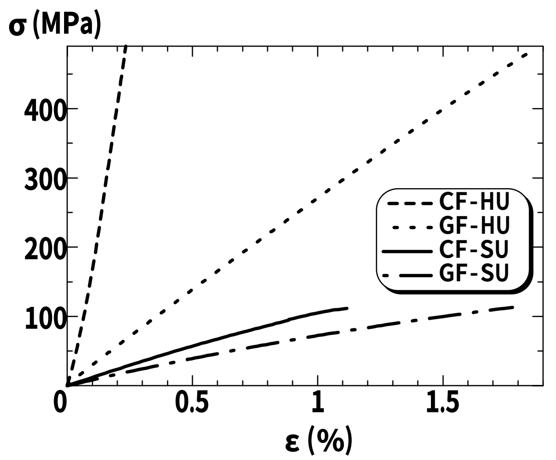


Figure 2: Stress – strain relationship for FRP test pieces

Table 1: Tensile test for test pieces of FRP

| | CF - HU | | GF - HU | | CF - SU | | GF - SU | |
|---|---|---|---|---|---|---|---|---|
| | Average | STDV | Average | STDV | Average | STDV | Average | STDV |
| Thickness (mm) | 0.654 | 0.096 | 2.949 | 0.143 | 3.372 | 0.596 | 4.614 | 0.617 |
| Width (mm) | 24.787 | 0.076 | 24.785 | 0.057 | 24.917 | 0.095 | 24.794 | 0.049 |
| Maximum load (kN) | 18.23 | 1.52 | 38.43 | 3.66 | 9.43 | 3.02 | 12.92 | 2.33 |
| Tensile strength (MPa) | 1124 | 77 | 527.0 | 57.0 | 117.1 | 41.8 | 112.9 | 12.2 |
| Elastic modulus (GPa) | 64.20 | 2.27 | 28.16 | 1.65 | 15.24 | 4.88 | 7.669 | 0.569 |
| Ultimate strain (%) | 1.76 | 0.11 | 1.87 | 0.14 | 0.78 | 0.19 | 1.48 | 0.18 |

## ANTISYMMETRICAL LOADING TEST FOR COLUMNS

### *Specimens*

Table 2 shows the properties of specimens. Four specimens were prepared. The dimension of these all four specimens was 300mm wide and 300mm deep and the shear span ratio is 1.5. The parameters were FRP reinforcements, which were sprayed-up CFRP (CF-SU), sprayed-up GFRP (GF-SU), carbon fiber sheet (300g/m$^2$) with one layer (CF-HU), and glass fiber sheets (444g/m$^2$) with four layers (GF-HU). Resin of vinyl ester was utilized for all specimens. The amount of FRP reinforcements were designed so as for the FRP stiffness (elastic modulus times thickness) to be equal. Deformed rebars D13 (yield strength = 341MPa) and D6 (yield strength = 413MPa) were used as main bars and hoops, respectively. The designed normal weight concrete strength was 30MPa. The maximum diameter of the aggregates was 20mm. The measured compressive strength at the loading age is 34.2MPa. Table 3 shows the material properties of FRP. Regarding FRP, the material property was identical to Table 1. The properties of sheets are calculated by considering the cross-section as the designed thickness of only the fiber.

Table 2: Column specimens

| Specimen | Section (mm) | Main bar | Hoops | | FRP (Specified values) | |
|---|---|---|---|---|---|---|
| | | | Arrangement | $p_w$ (%) | Elastic modulus (GPa) | Thickness |
| CF-HU | 300×300 | 12-D13 | D6@160 | 0.13 | 240 | 0.167mm×1 |
| GF-HU | | | | | 54 | 0.163mm×4 |
| CF-SU | | | | | 12 | 3.0mm |
| GF-SU | | | | | 8 | 4.5mm |

Table 3: Mechanical properties of FRP

| ID | Tensile strength (MPa) | Elastic modulus (GPa) | Ultimate strain (%) |
|---|---|---|---|
| CF-HU | 4451* | 254.1* | 1.76 |
| GF-HU | 2378* | 127.1* | 1.87 |
| CF-SU | 117.1 | 15.24 | 0.78 |
| GF-SU | 112.9 | 7.669 | 1.48 |

* For sectional area of only fiber (not included resin)

### *Loading System and Instrumentation*

Each specimen was subjected to anti-symmetrical bending moment in a cyclic manner. The drift angles were from 1/400 rad to 1/15rad. The axial force was kept constant at 63kN as the axial stress was 0.2 of concrete strength. Measuring items were horizontal and vertical displacements between the top and bottom stubs, and strains of main bars, hoops and FRP as shown in Figure 3. Tri-axial strain gages were used for measuring strains of sprayed-up FRP.

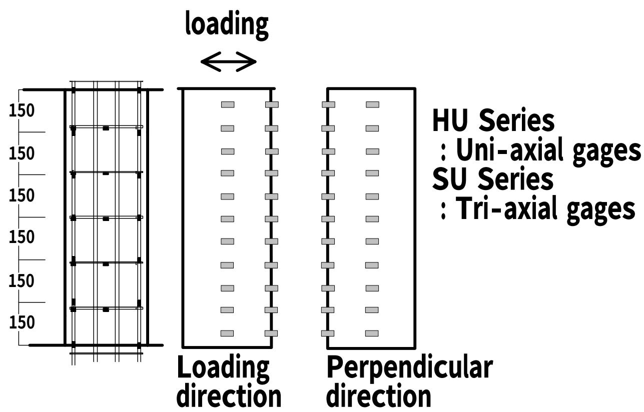


Figure 3: Location of strain gages

### *Ultimate Strength and Shear Force versus Drift Angle Curves*

Table 4 and Figure 4 show the test results and shear force versus drift angle curves, respectively. All four specimens were yielded in flexure. After that, FRP for CF-SU and GF-SU was ruptured at the drift angle, -1/20rad and +1/20rad, respectively. Both fiber sheet reinforcements and sprayed-up FRP reinforcements give the similar results on the effectiveness of shear reinforcements. As shown in Table 4, ${}_{e}Q_{y}$ for all four specimens were approximately the same as calculated bending capacity of 258.8kN. Figure 4 shows that GF-HU has the best performance on the deformation capability until the drift angle 1/20rad. The deformation capabilities declined in the order, CF-SU, GF-SU, and CF-HU, accordingly. The failures for sprayed-up specimens are shown in Photo 3 and 4.

Table 4: Results of column test

| Specimen | | CF-HU | GF-HU | CF-SU | GF-SU |
|---|---|---|---|---|---|
| Load at yielding ${}_{e}Q_{y}$ (kN) | | 267.1 | 264.6 | 257.4 | 268.4 |
| Maximum load ${}_{e}Q_{max}$ (kN) | pos | 274.2 | 296.6 | 300.0 | 285.6 |
| | neg | 277.2 | 321.0 | 303.2 | 302.0 |
| | average | 275.7 | 308.8 | 302.0 | 293.8 |
| Drift angle at yielding $R_{y}$ ($\times 10^{-2}$rad) | | 0.91 | 0.77 | 0.60 | 0.83 |
| Drift angle at ultimate $R_{u}$ ($\times 10^{-2}$rad) | pos | 2.47 | >6.67 | 5.00 | 3.27 |
| | neg | 3.00 | >5.00 | 3.32 | 2.01 |

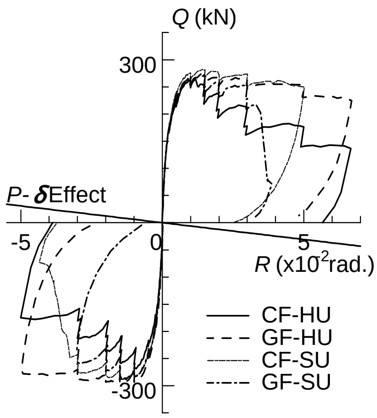

Figure 4: $Q$-$R$ curves


Photo 3: CF-SU


Photo 4: GF-SU

## *FRP Strain Distributions*

Figure 5 illustrates strain distributions of specimens CF-HU and CF-SU at peak steps of each drift angle. The strains for sprayed-up FRP specimens at loading direction surface were small. Regarding strains at the corners of specimens, sheet reinforced specimens had few negative strains. However,

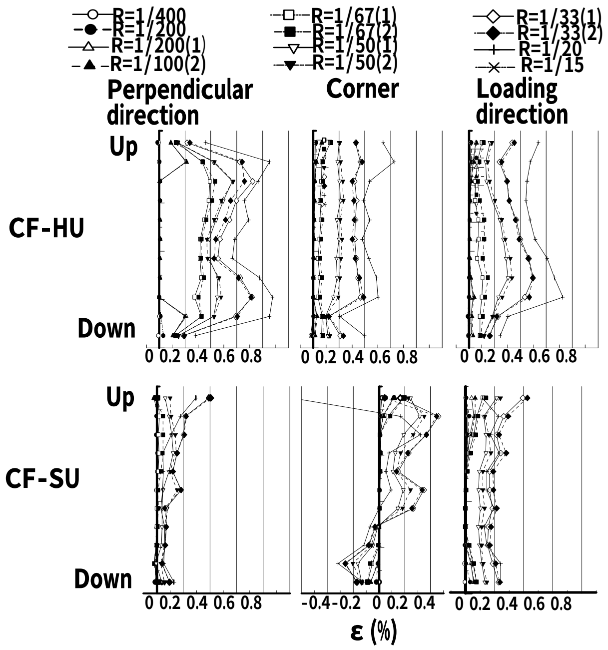

Figure 5: Strain distributions of FRP

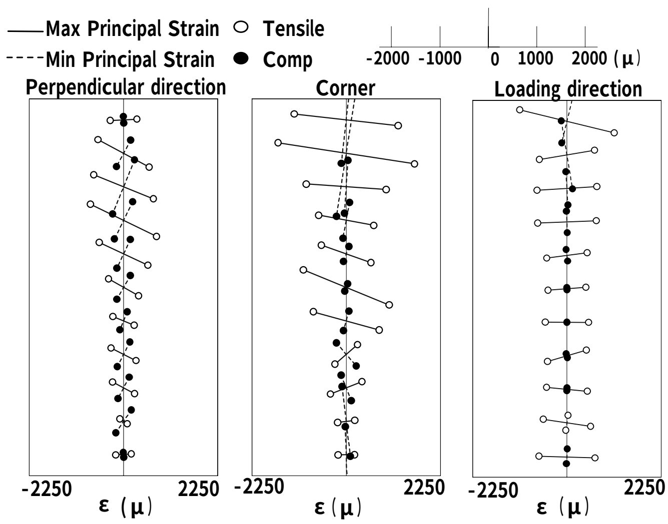

Figure 6: Principal strains of sprayed-up FRP

sprayed-up FRP specimens had many negative strains. It shows that the flexural stiffness of sprayed-up FRP specimens is larger than the one of sheet reinforced specimens and that compression strains at the surface of corner portions occurs.

The principal strains and those directions of FRP of specimen CF-SU at the drift angle, 1/50rad are shown in Figure 6. At the principal strain directions for sprayed-up FRP specimens, horizontal tension and vertical compression at perpendicular face to the loading direction occurred. The strains at the corner portions show tension and compression at the same face to the loading direction. However, strains at the ends of specimens were influenced by the stubs in some degrees. The strain directions were distorted because of this influence. In the loading direction, both the maximum and minimum principal strains were tension around the top of the column at the positive drift angle and around the bottom of the column at the negative drift angle.

## BOND AND ANCHOR TEST BETWEEN FRP AND CONCRETE

Sprayed-up FRP has flexibility for the concrete surface at the construction site. FRP spray-on methods were studied by providing slits or anchor bolts to bond and anchor FRP on the concrete. Two different series of experiments were carried out, which were bond test by double shearing and anchor test for meeting corners between beams and slabs or columns and walls.

### *Specimens for Bond Test*

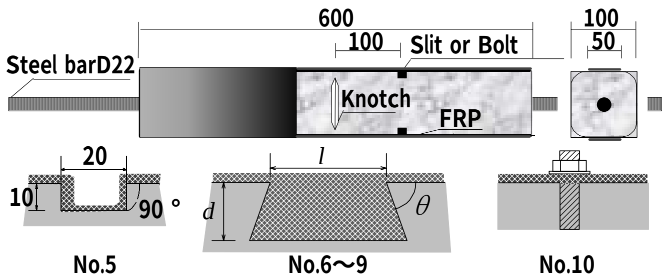

Figure 7: Bond test specimen

Specimens for bonding between FRP and concrete were prepared as shown in Figure 7. The specimen consists of a concrete prism (100 x 100 x 600mm) cracked at the center, using a hammer on the notch, after the reinforcing with FRP. The two steel bars also have no connection, which means that the two prisms are connected only through the FRP. Specimens No.1 through No.4 and No.11 had no slits. In order to investigate each FRP bond behavior, FRP was sprayed on specimens under the exact same conditions as column specimens for specimens No.1 through No.6. The FRP of specimens with slits was expected mechanical bearing to concrete. The parameters of specimens were slit types, the number of slits, and diameters of anchor bolts. The list of specimens is shown in Table 6 with test results. Concrete for No.1 through No.6 and No.7 through No.11 was normal weight concrete with compressive strength of 34.2 MPa and 25.7 MPa, respectively. The specified thickness o f sprayed-up FRP was 8.0mm for No.7 through No.11. Static tensile load was applied with displacement controlled 2MN loading machine. Load and crack width of notch at center of specimens were measured. FPR strains were measured by strain gages with the interval of 15mm.

### *Results and Analysis of Bond Test*

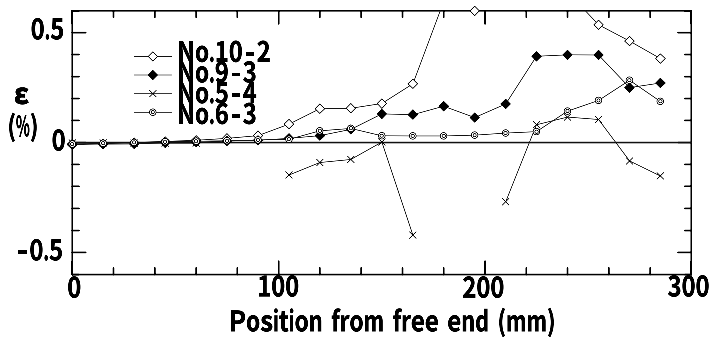

Figure 8: Strain distributions of FRP

Table 5 and Figure 8 show a list of results and FRP strain distribution at maximum displacement, respectively. In specimens with no slit, No.1 through No.4, the maximum loads of sprayed-up FRP specimens were larger than the ones of specimens with FRP sheets. Since FRP stiffness is equal to or larger than FRP sheets, the bond strength of FRP in the sprayed-up method is equal to or larger than the ones in sheet reinforcements. Because specimens No.5, which have a slit without filling FRP, showed bond failures, there is no indication that a slit works as FRP anchor. From the strain distribution (Figure 8) for specimen No.5, strains were negative values around the slit. It indicates that flexural force occurred to FRP and that FRP was peeled along the slit and lost bond. According to specimens No.6, which have an angled slit as a parameter (Figure 7), fixative behavior was sufficient. The strain distribution indicates that there was no compression strain. The stiffness between the slit and FRP were improved by filled with FRP in the slit. The mechanical bearing between a slit and FRP was capable.

The fixative behaviors for specimens No.7 through No.9 were sufficient, though the bonding strengths for these specimens No.7 through No.9 were unknown by concrete failure. Since specimens with slit angle 90 degree did not failed in bond, filling FRP in slits or increasing the stiffness of FRP in the slit makes the bond behavior more capable, comparing to specimens No.5 and No.6. Slit depth 10mm or deeper can give the sufficient FRP bonding, because specimen No.9-1 failed in bond. In series No.10, which has anchor bolts, FRP fixed by M16 bolts was ruptured at a location where the anchor bolt was fastened. The anchor bolt diameter was too large to the FRP width. For FRP fixed by M6 bolts, the anchor bolts themselves were ruptured. M6 bolts were too small to the FRP width. It is certain that there should be an appropriate anchor bolt size to FRP width.

Table 5: Results of bond test

| No. | Slit, Bolt | | | | ID | Maximum load (kN) | Failure pattern* |
|---|---|---|---|---|---|---|---|
| | Width *l*(mm) | Depth *d*(mm) | Angle θ | Number | | | |
| 1-1~3 | - | | | | CF-HU | 16.58 | BF |
| 2-1~3 | | | | | GF-HU | 14.40 | |
| 3-1~3 | | | | | CF-SU | 26.27 | |
| 4-1~3 | | | | | GF-SU | 15.91 | |
| 5-1<br>5-2 | 20 | 10 | 90 deg | 1<br>2 | CF-SU | 18.43<br>16.55 | BF→FR |
| 5-3<br>5-4 | | | | 1<br>2 | GF-SU | 14.82<br>15.09 | BF<br>BF→FR |
| 6-1<br>6-2<br>6-3 | 20 | 10 | 75 deg<br>60 deg<br>45 deg | 1 | GF-SU | 33.75<br>19.78<br>18.25 | FR |
| 7-1<br>7-2<br>7-3 | 40 | 5<br>10<br>20 | 75 deg | | GF-SU Thick-ness 8.0mm | 33.06<br>36.67<br>37.39 | CF |
| 8-1<br>8-2<br>8-3 | 40 | 5<br>10<br>20 | 90 deg | | | 29.04<br>37.84<br>33.70 | |
| 9-1<br>9-2<br>9-3 | 20 | 5<br>10<br>20 | 75 deg | | | 33.55<br>38.59<br>36.36 | BF<br>CF |
| 10-1<br>10-2<br>10-3 | Bolt M6<br>Bolt M12<br>Bolt M16 | | | | | 30.89<br>44.72<br>45.45 | BF→AR<br>CF<br>FR |
| 11 | - | | | | | 28.08 | BF |

* BF: Bond failure FR: FRP Rupture CF: Concrete failure AR: Bolt failure

***Specimens for Anchor Test at Meeting Corner***

Figure 9 shows a typical specimen. The loading was a tensile test fixing one end. The parameter of the specimens were slit sizes, anchor bolt diameters, and the number of anchor bolts. The concrete compressive strength was 25.7MPa of normal weight concrete. The same type of FRP as No.7 through

No.11 of the bond test mentioned before was used.

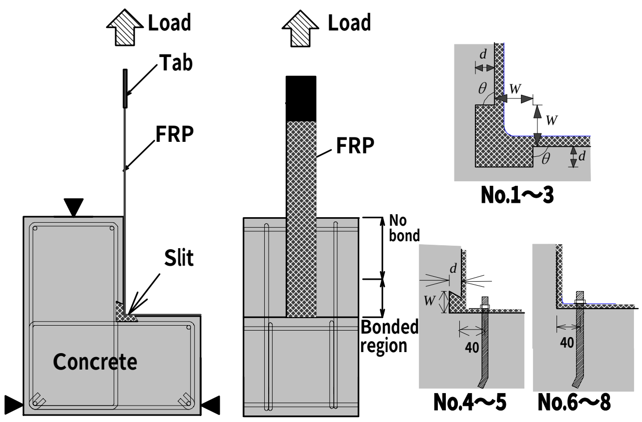


Figure 9: Anchor test specimen

Photo 5: Specimen


Photo 6: After loading

***Results and Analysis of Anchor Test***

The test results are shown in Table 6. The results of the anchor test indicate that specimens with a slit obtained sufficient anchoring because these specimens failed in FRP ruptured or concrete failure. Specimens No.1 and No.2 had FRP rupture. This indicates that a slit angle 90 degrees gives sufficient anchoring behavior of FRP. Specimens with anchor bolt reinforcement had 2 to 2.5 times as large maximum load as specimens with no anchor No.9, because the anchor bolt fixed the FRP at the bottom. However, specimens with slit had extremely larger maximum load than the ones with anchor bolt reinforcement. It indicates that slit reinforcement is better method to anchor FRP.

Table 6: Results of anchor test

| No. | Slit, Bolt | | | | ID | Maximum load (kN) | Failure Patter |
|---|---|---|---|---|---|---|---|
| | Width *w* (mm) | Depth *d* | Angle $\theta$ | | | | |
| 1 | 40 | 10 | 90 deg | | GF-SU Thickness 8.0mm | 30.72 | FRP Rupture |
| 2 | | | 75 deg | | | 32.67 | FRP Rupture |
| 3 | 20 | | | | | 37.05 | FRP Rupture |
| 4 | 40 | 10 | 75 deg | M12 | | 28.73 | FRP Rupture |
| 5 | 40 | 10 | 75 deg | M16 | | 31.83 | Concrete failure |
| 6 | Bolt M12 | | | | | 12.86 | FRP rupture |
| 7 | Bolt M16 | | | | | 18.87 | |
| 8 | Bolt M6×8 | | | | | 25.22 | Bolt yield |
| 9 | - | | | | | 6.70 | Debonding |

## CONCLUSIONS

This strengthening method by sprayed-up carbon and glass fibers with vinyl ester resin is possible to apply to concrete structures. When sprayed-up CFRP that was the same strength as $300g/m^2$ one layer of carbon sheet was expected, approximately 6.5mm of FRP thickness needed to be sprayed. There was no large difference on deformations, ultimate strengths, or FRP strains between columns reinforced by FRP sheet and sprayed-up FRP. The bond and anchor strength was improved by filling FRP into a concrete slit or by angling a concrete slit.

This study verified that sprayed-up FRP strengthening was possible to expect the same structural behaviors as the fiber sheet reinforcement. The sprayed-up FRP strengthening method is inexpensive and simple to construct. This method will facilitate the future strengthening for concrete structures.