SPRAYED FIBER-REINFORCED POLYMERS FOR STRENGTHENING OF CONCRETE STRUCTURES

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SUMMARY

A new repair and strengthening method by sprayed 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 reinforced concrete (RC) columns / beams and anchor / bond test between sprayed fiber-reinforced polymer (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 and T-shape beams was carried out for the purpose of confirming fundamental behaviours of RC structures strengthened by sprayed FRP system.

As the results, it can be recognized that the similar shear strengthening effect is obtained in either way sprayed FRP or fiber sheet strengthening. Anchor method due the advantage of sprayed FRP's flexibility is investigated. 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 with fiber sheet. By filling the FRP to the slit, the mechanical bearing can be expected. From the T-shape beam test results, failure of FRP at the meeting corner between beam and slab is not observed by FRP filled slit anchoring.

1. 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 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 sprayed FRP strengthening method and the results of column and T-shape beam test under the anti-symmetrical loading are reported. In addition, the bond behavior between FRP and concrete, and anchoring behavior using slit (groove) filled by sprayed FRP are reported.

2. OUTLINE OF SPRAYED FRP STRENGTHENING METHOD

Figure 1 illustrates the idea of the sprayed 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 strengthened. 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, such as columns, beams, walls, and slabs, are monolithic since it is possible to strengthen an entire interior structures in building structures.

The installing procedure of the sprayed FRP 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 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.

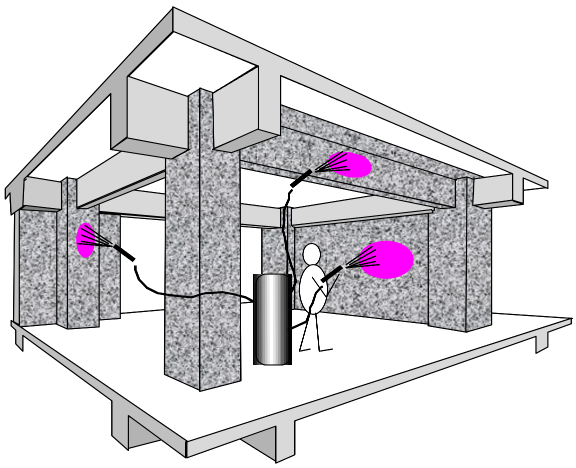


Figure 1 Sprayed FRP strengthening **Photo 1 Sprayed fiber** **Photo 2 Surface curing**

3. MECHANICAL PROPERTIES OF SPRAYED FRP

A total of sixty coupon specimens of each sprayed 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 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 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 (σ – ε) diagram, 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 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, σ– ε relationships for sprayed FRP is not perfect linear.

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

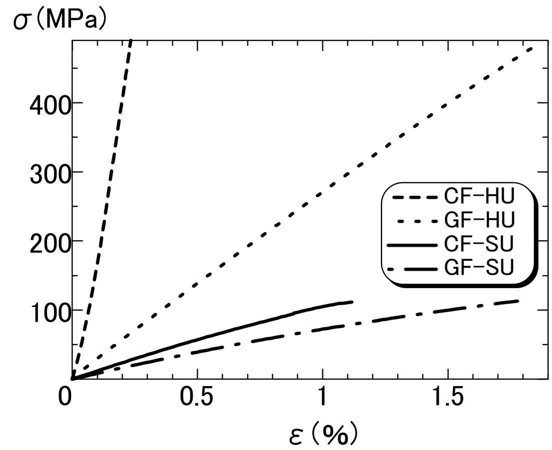


Figure 2 Stress – strain relationship for FRP test pieces

4. ANTISYMMETRICAL LOADING TEST FOR COLUMNS

4.1 Specimens

Table 2 shows the properties of column 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 CFRP (CF-SU), sprayed 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)

4.2 Loading System and Measurements

Each specimen was subjected to anti-symmetrical bending moment in a cyclic manner. The drift angles were from 1/400rad. 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 FRP.

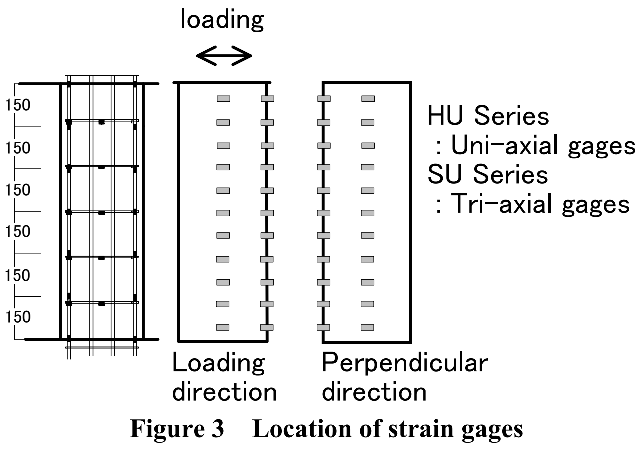


Figure 3 Location of strain gages

4.3 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 FRP reinforcements give the similar results on the effectiveness of shear reinforcing. As shown in Table 4, ${}_eQ_y$ 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 decline in the order, CF-SU, GF-SU, and CF-HU, accordingly. The failures for sprayed FRP 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 ${}_eQ_y$ (kN)		267.1	264.6	257.4	268.4
Maximum load ${}_eQ_{max}$ (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

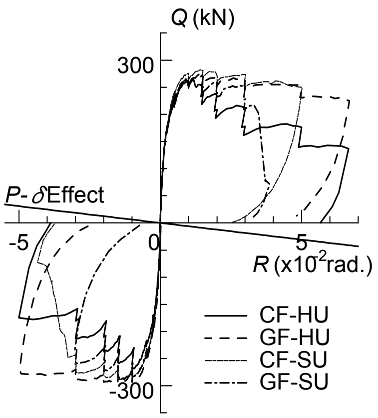


Figure 4 *Q-R* curves

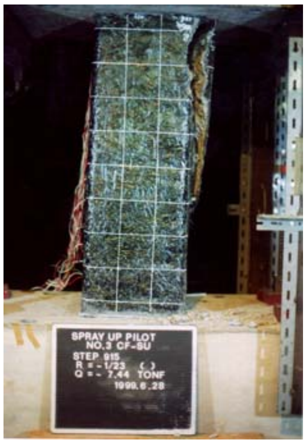


Photo 3 CF-SU

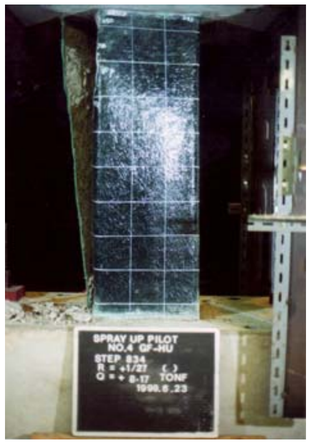


Photo 4 GF-SU

5. ANCHOR / BOND TEST BETWEEN SPRAYED FRP AND CONCRETE

Sprayed FRP has flexibility for the concrete surface at the construction site. It has been known that structural behaviors of T-shape beams strengthened by fiber sheets are influenced by conditions of sheet anchoring at the meeting corner between beam and slab [1]. In this study, it is proposed that sprayed FRP is anchored at the meeting corner using "FRP filled slits". Figure 5 shows an image of FRP anchoring method at the meeting corner. In this method, there is a merit that steel materials are not utilized. In this study, bond test by double shearing type specimens are conducted in order to investigate the effectiveness of FRP filled slits. The test variables are size of slits.

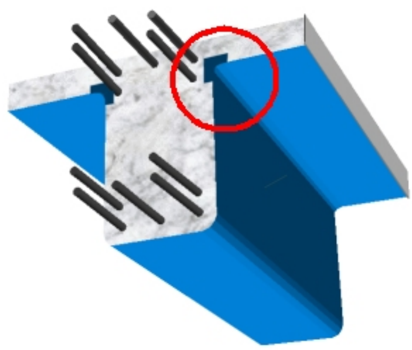


Figure 5 FRP filled slit anchoring

5.1 Specimens

Specimens for anchor / bond test between FRP and concrete were prepared as shown in Figure 6. 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 had no connection, which means that the two prisms were connected only through the FRP. Specimens No.1 had no slits in order to investigate pure bonding strength between FRP and concrete. Specimens No.2 through No.4 had FRP filled slits. The FRP at the slits was expected mechanical bearing to concrete. The parameters of specimens were depth of slits (5, 10, 20mm). The list of specimens is shown in Table 5 with test results. Three specimens were tested for one test variable.

Concrete for anchor / bond specimens was normal weight concrete with compressive and tensile strength of 32.8MPa and 2.70MPa, respectively. Tensile load was applied at the both steel bar ends with displacement controlled 2MN loading machine. Load and crack width of notch at the center of specimens were measured. FPR strains were measured by strain gages as shown in Figure 6.

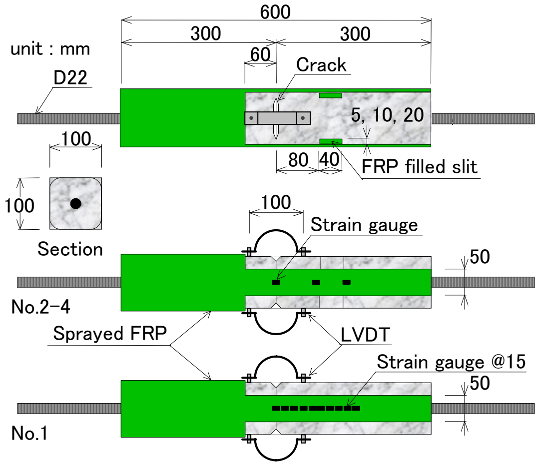


Figure 6 Anchor / bond test specimen

Table 6 summarizes the tensile test results of sprayed FRP test pieces for anchor / bond test specimens. The specified thickness of sprayed FRP using glass fiber with vinyl ester resin was set to 3.0mm.

Table 5 List of anchor / bond specimens

Specimen	Slit		At maximum load		Failure type
	Width (mm)	Depth (mm)	Load (kN)	Crack width (mm)	
No.1-1	No slit		20.8	1.13	Bond failure
-2			26.3	1.48	Bond failure
-3			14.8	0.75	Bond failure
No.2-1	40	5	24.1	1.22	Concrete shear
-2			24.2	1.78	FRP rupture
-3			27.1	1.41	Concrete shear
No.3-1		10	-	-	FRP rupture
-2			23.0	1.21	Concrete shear
-3			31.2	1.78	Concrete shear
No.4-1		20	30.2	1.46	FRP rupture
-2			16.9	0.79	FRP rupture
-3			26.3	1.37	FRP rupture

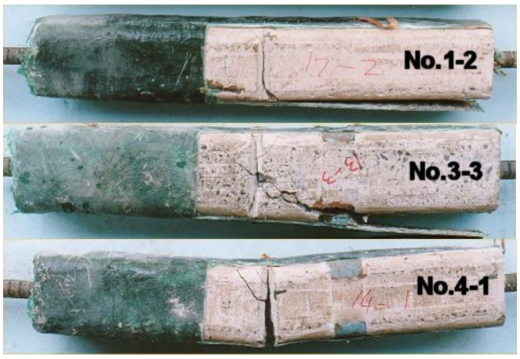
Table 6 Tensile test results for test pieces (GFRP)

Width (mm)	Thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)
24.8	3.99	67.2	8.02	1.24

5.2 Failure Type and Maximum Load

Specimens No.1 without slit failed by debonding of FRP from concrete. Specimens from No.2 to No.4 failed by FRP rupture or concrete shear failure. Typical failures are shown in Photo 5. The maximum load for specimens No.1, i.e., bond strength between sprayed FRP and concrete is 20.6kN in the average of three specimens. Comparing with the bond strength of carbon fiber sheet having same rigidity, the bond strength is almost 80% of analytical bond strength by literature [2] of 25.7kN.

The anchoring strength of FRP filled slit is not clear, because specimens from No.2 to No.4 failed by FRP rupture or concrete shear failure. However, the slit depth of 5mm is sufficient to cause rupture of FRP itself. The average of maximum load of three specimens of No.2 is 97% of tensile strength obtained by coupon tensile specimens.



No.1-2 : Bond failure

No.3-3 : Concrete shear

No.4-1 : FRP rupture

Photo 5 Anchor / bond specimens after loading

5.3 FRP Strain Distributions

Figure 7 shows strain distributions of FRP for each specimen. X-axis indicates the distance from the center of specimens. The slits locate between 80mm and 120mm for specimens No.2 through No.4. In specimen No.1, it is observed that a section having the slope of strain distribution moves from the center toward the end of the specimen as increasing the load. This phenomenon is caused by debonding of FRP. In specimens No.2 - No.4, the strains in the range beyond the slits is very small. From these results, it is recognized that the FRP filled slits have efficiency to anchor the FRP.

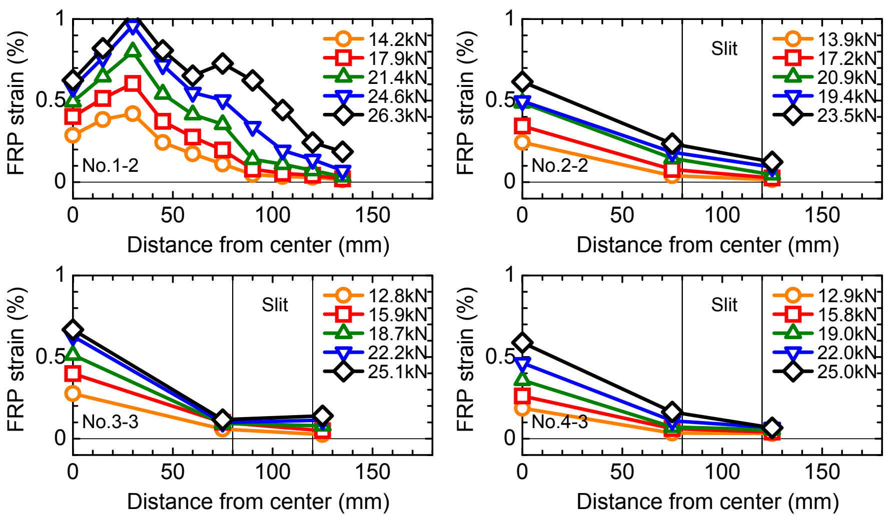


Figure 7 Strain distributions of FRP

6. ANTISYMMETRICAL LOADING TEST FOR T-SHAPE BEAMS

6.1 Specimens

Figure 8 shows the dimensions and the details of beam specimens. The specimens were modeled in 1/3 scale of actual beams with slabs. The dimension was 300mm wide and 200mm deep and the shear span ratio is 2.0. The width and thickness of slabs were 500mm and 50mm, respectively. The test variable is type of FRP anchorage at the meeting corner of beam and slab. In specimen No.1 and No.2, FRP was anchored by FRP filled slits. In specimen No.2, anchor bolts M12 were also set to slab surface. In specimen No.3, FRP was anchored by only M12 bolts to slab surface. Steel blocks were also used to anchor the FRP in specimen No.4.

The thickness of FRP using glass fiber with vimyl ester resin are designed to 3mm so as for the FRP rigidity (elastic modulus times thickness) to be equal with the carbon fiber sheet strengthening of specimen No.22 and No.23 of literature [1]. Deformed rebars D13 (yield strength = 324MPa) and D4 (yield strength = 218MPa) were used as main bars and stirrups, respectively. The designed normal weight concrete strength was 24MPa. The maximum diameter of the aggregates was 15mm. The measured compressive and tensile strength at the loading age is 26.9MPa and 2.02MPa, respectively.

6.2 Loading System and Measurements

Each specimen was subjected to anti-symmetrical bending moment in a cyclic manner. The drift angles were from 1/400rad. to 1/20rad. Measuring items were horizontal and vertical displacements between the top and bottom stubs, and strains of main bars, stirrups and FRP.

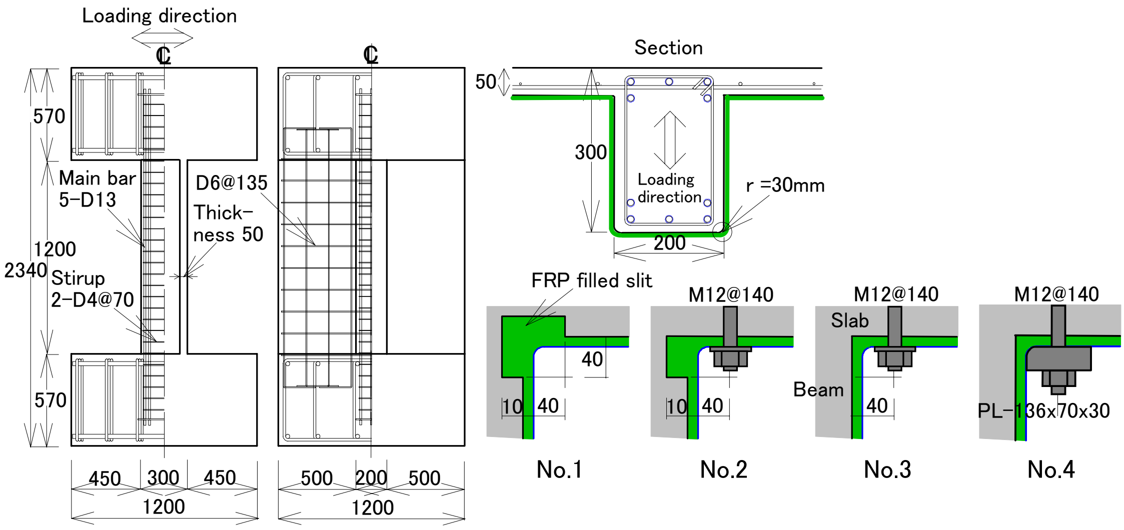


Figure 8 T-shape beam specimen

6.3 Failure Progress

Specimens after loading are shown in Photo 6. All specimens had flexural yielding at the loading cycle of 1/100rad. At the loading cycle of 1/50rad., small cracks of FRP took place. Finally, the load decreased by rupture of FRP.

In specimen No.3, cracks of FRP around the anchor bolts took place at the first loading cycle of 1/50rad. At the second loading cycle, FRP rupture at the meeting corner was observed, and FRP had debonding on the sides of beam. In specimen No.4, FRP cracked around the steel blocks at the second loading cycle of 1/50rad. After that, rupture of FRP expanded along the shear cracks of concrete. In specimen No.1 and No.2, cracks of FRP around the beam corner at the end of beam took place at the second loading cycle of 1/50rad. At the loading cycle of 1/33rad., FRP ruptured along the beam corner toward the axial direction. Failure of FRP at the meeting corner was not observed.

Shear force versus translational angle (drift angle) relationships are shown in Figure 9. The angle in which the remarkable decrement of shear force was observed is in the order of specimen No.2 > No.1 > No.4 > No.3. The effectiveness of FRP filled slit for anchoring of FRP is also recognized in the beam test.

Photo 6 Beam specimens after loading

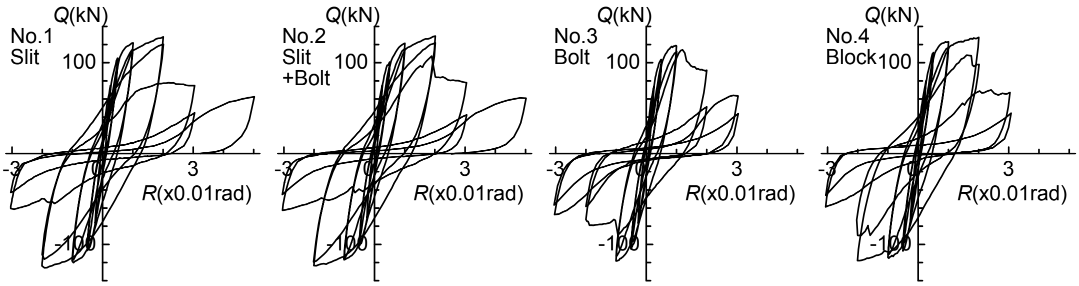


Figure 9 Shear force - translational angle curve

6.4 Comparison between Sprayed FRP and Carbon Fiber Sheet Strengthening

Shear force versus translational angle curves are compared with those of specimens strengthened by carbon fiber sheet. As reported in literature [1], T-shape beam specimens having same dimensions and material strength with this study have tested to investigate the efficiency of carbon fiber sheet strengthening. The specimen No.11 was not strengthened by sheet, and specimen No.22 and 23 were strengthened by 1 layer of carbon fiber sheet of 200g/m^2. In both specimen No.22 and No.23, fiber sheet was anchored at the meeting corner by steel angles and anchor bolts. In specimen No.22, the anchor bolts were set to both beam and slab faces. In specimen No.23, the sheet was anchored only to the slab face.

Skeleton curves for these specimens are shown in Figure 10. Specimen No.11 failed by shear without flexural yielding. All specimens No.1 - No.4 change failure mode to flexural yielding type. Strengthening effect by sprayed FRP is recognized. Comparing the specimens No.1 - No.4 with specimens No.22 and No.23, the behaviors are almost the same until 1/50rad. After the loading of 1/33rad., sprayed FRP

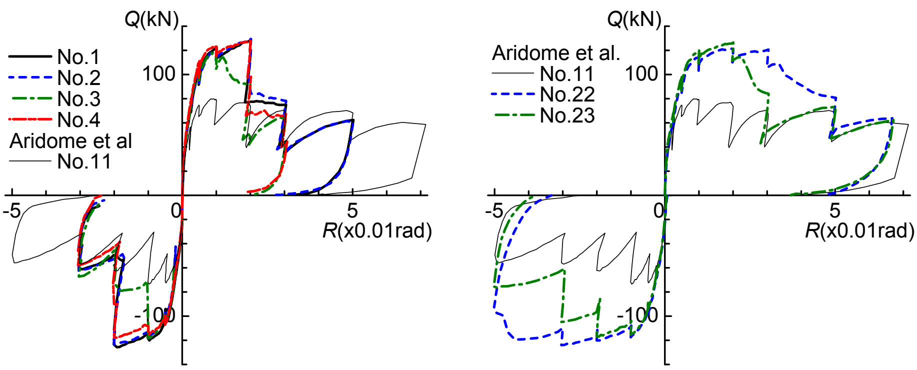


Figure 10 Comparing of skeleton curves between sheet strengthening

strengthened specimens show brittle behavior rather than sheet strengthened specimens. This is caused by rupture of FRP itself at the corner of beam. The tensile strength per unit width of sprayed FRP and carbon fiber sheet is 268 and 541kN/mm, respectively.

6.5 FRP Strain Distributions

FRP strain distributions at the peak load of each loading cycle are shown in Figure 11. The left side diagrams show ones for specimen No.2, the right sides are for specimen No.3. The upper diagrams indicate the distributions at the side of beam, and the lowers are at the corner of beam. The maximum FRP strain is about 0.3 to 0.4%. In specimen No.2, the strains of the corner at the ends of the beam are larger corresponding to actual failure mode, FRP rupture at the corner. In specimen No.3, negative strains take place because of FRP debonding from side of beam.

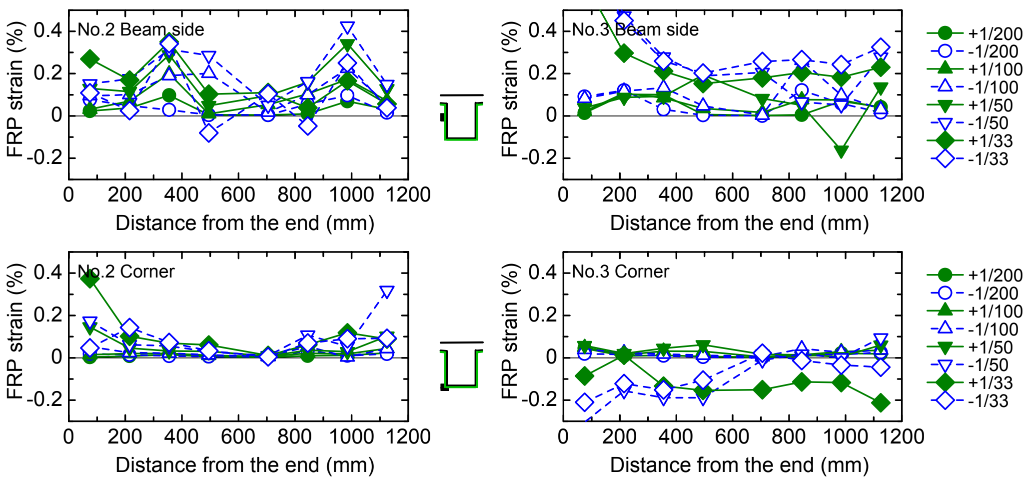


Figure 11 Strain distributions of FRP

7. CONCLUSIONS

The anti-symmetrical loading test of rectangular columns and T-shape beams was carried out for the purpose of confirming fundamental behaviours of RC structures strengthened by sprayed FRP system. In addition, anchor / bond test by double shearing type specimens were conducted in order to investigate the effectiveness of FRP filled slits anchoring. The following results were obtained.

(1) Strengthening method by sprayed carbon and glass fibers with vinyl ester resin is possible to apply to concrete structures.
(2) There was no large difference on deformations, ultimate strengths, or FRP strains between columns reinforced by sprayed FRP and continuous fiber sheet.
(3) Both results of anchor / bond test and T-shape beam test indicate that FRP filled slit is effective for anchoring of FRP to concrete. The slit depth of 5mm is sufficient to cause rupture of FRP itself.
(4) Failure of FRP at the meeting corner between beam and slab is not observed by FRP filled slit anchoring. FRP ruptured at the beam corner at the angle of 1/50rad.

8. REFERENCES

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[2] Nakaba, K., Kanakubo, T., et.al. (2001), "Bond Behavior between Fiber-Reinforced Polymer Laminates and Concrete", *ACI Structural Journal*, Vol.98, No.3, May-June, pp.359-367