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- Technical Paper -

SEISMIC RETROFITTING OF REINFORCED CONCRETE COLUMNS WITH CONTINUOUS FIBER ROPE

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ABSTRACT

This study deals with a new method for seismic retrofitting of reinforced concrete columns using a new type of continuous fiber material made in the form of rope. It is made with aramid fiber rope without epoxy resin. Continuous fiber rope was retrofitted on the surface of existing reinforced concrete column. Thereafter, concrete jacketing was applied to protect continuous fiber rope. A series of reinforced concrete columns retrofitted by continuous fiber rope and concrete jacket were under reversed cyclic loading. Through the tests, failure behavior and ductility improvement of the specimens were discussed.
Keywords: seismic retrofitting, continuous fiber rope, ductility, concrete jacketing

1. INTRODUCTION

Seismic retrofitting of reinforced concrete structures using continuous fiber reinforcing materials, such as carbon or aramid sheet, has become popular for its simple handling and lightweight. This study focuses on a new method of seismic retrofitting for reinforced concrete columns using a new type of continuous fiber material made in the form of rope. Continuous Fiber Rope (CF Rope) is distinguished from other types of continuous fiber reinforcement for concrete, such as rod, grid and sheet, by its non-epoxy usage. Therefore, it can be arranged in existing structural member by hand easily without impregnating process of epoxy resin.

So far, the authors have verified that CF Rope can be used as shear reinforcement embedded in concrete [1]. In this study, we apply this CF Rope on the surface of existing concrete member with concrete jacketing. Concrete jacketing is expected to protect CF Rope during service stage and to effectively transfer stress to CF Rope just after cracking.

A series of reinforced concrete column specimens retrofitted by CF Rope and concrete jacket were under a reversed cyclic loading test. Through the experiment, the failure behavior of the column specimens was discussed and their ductility improvement was investigated. Test results are also compared with those of RC columns retrofitted with continuous fiber sheet (CF Sheet) that had been done by the authors [2].

2. CONTINUOUS FIBER ROPE

The CF Rope used in this study (Fig.1) was made from aramid fiber. It consists of 9 bundles of fiber, twisted together in groups of three. CF Rope was coated by resin for ease of handling. Properties of fiber are presented in Table 1.

Fig.1 Continuous fiber rope

Table 1 Properties of fiber

Density (g/cm^3)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)	Ultimate strain (%)
1.39	3410	74000	4.5

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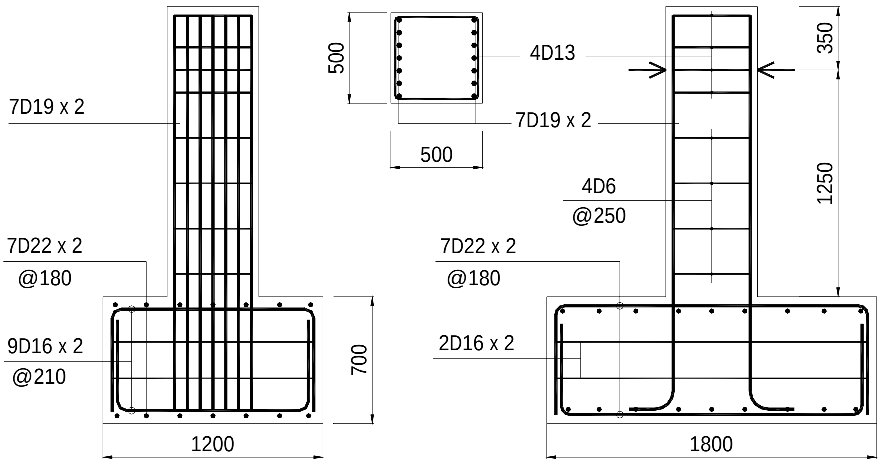

Fig.2 Details of the column specimens

Tensile properties of CF Rope were determined by carrying out uniaxial tensile test [3]. A total number of 5 test pieces were tested. Taking the average values of the 5 test pieces, the test results are presented in Table 2. Nominal cross sectional area of CF Rope is taken as 17.19 mm^2, which is determined by measuring the weight of 1m of CF Rope and divided by the density of the rope.

Table 2 Tensile properties of CF Rope

Tensile capacity (KN)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)	Ultimate strain (%)
28.7	1660	53300	2.8

3. COLUMN SPECIMENS WITH CONTINUOUS FIBER ROPE AND CONCRETE JACKET

3.1 Column Specimens

The series of specimens consists of 3 identical columns; the control specimen (column No.0) was not retrofitted while two other specimens (column No.1 and column No.2) were retrofitted by CF Rope and concrete jacket.

Table 3 Parameters of column specimens

Items	Unit	Values
Concrete strength	N/mm^2	26
Tensile strength of reinf.	N/mm^2	384
Reinforcement ratio	%	0.9
Shear-to-flexural capacity ratio		0.90

The column specimens were designed to fail in shear. Details of the column specimens before retrofitting are shown in Fig.2 and Table 3.

3.2 Retrofitting of CF Rope and Concrete Jacket

Column No.1 and column No.2 were retrofitted by CF Rope and concrete jacket. Before the winding of rope, the surface of column was grinded by a grinding machine to ensure bonding between the original concrete of column and concrete jacket. In order to prevent stress concentration in CF Rope, the corners of the column were rounded also by grinding machine to the radius of approximately 17 mm. Then positions of winding rope were drawn on the column surfaces.

After the surface preparation, CF Rope was wound around the periphery of the column by hand without inducing tension. The rope was wound in a close line. Firstly, rope was wound from top to bottom of column and then wound back from bottom to top. Two ends of rope were connected to each other simply by making a knot. Epoxy resin was not used to bond or to anchor CF rope on the concrete surface. The arrangement of rope is shown in Fig.3.


Fig.3 Arrangement of CF Rope (No.1)

After winding rope, forms were set around the column and concrete jacket of 40 mm thick with maximum aggregate size of 13 mm was cast outside the column part. The concrete used for jacket was normal concrete, which was designed to have the same compressive strength as the original column concrete. In mechanical aspect, the concrete jacket is expected to effectively transfer tensile stress to CF rope by bonding mechanism just after cracking. On the other hand, in real structures, the concrete jacket can protect CF Rope from environmental attack or collision. Concrete jacket was cast from footing up to the height close to the loading point of column. Figure 4 shows the column specimen with concrete jacket.

Fig.4 Jacketing for column

Details of the retrofitted column specimens are shown in Table 4. Compressive strength of concrete jacket was tested on the day of the loading test of the column specimen.

Table 4 Details of retrofitted specimens

Specimen name	Spacing of CF Rope (mm)	Strength of concrete jacket (N/mm^2)
No.1	100 (double)	26
No.2	200 (double)	22

4. REVERSED CYCLIC LOADING TESTS OF THE COLUMN SPECIMENS

4.1 Test Setup and Method

The specimens were tested under reversed cyclic loading. The load was applied at the height of 1250 mm of column from the footing. Firstly, the specimens were loaded until yielding of longitudinal reinforcement was observed (P_y). The displacement of column at loading point at this stage was defined as the yield displacement (δ). Thereafter, reversed cyclic load was applied to the column incrementally under deformation control, such as $+1\delta, -1\delta, +2\delta, -2\delta, +3\delta, -3\delta$. At each deformation step, three cycles of loading were repeated. Failure of the member is defined when its bearing capacity is reduced to 80% of its maximum load. Test setup of the specimens is shown in Fig.5.

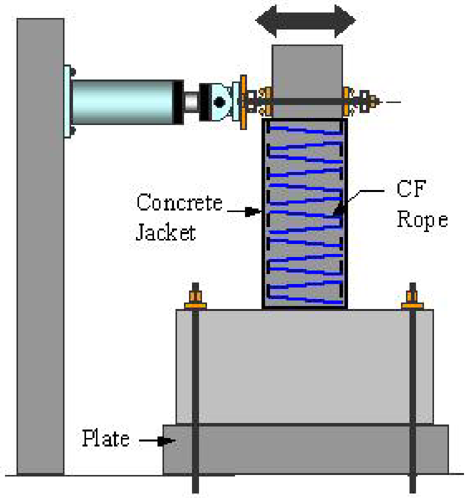

Fig.5 Test setup for column specimen

4.2 Test Results and Discussions

(1) Load – Displacement characteristics

The test results of maximum displacements and maximum loads of the three column specimens are presented in Table 5. It can be seen that, the maximum loading capacity of the three specimens are almost the same. It means that the ultimate capacity of the column is determined by the dimension of original reinforced concrete column and not influenced by the retrofitting of CF Rope and concrete jacket.

Table 5 Test results

Items	Unit	No.0	No.1	No.2
Max. load	KN	304	309	315
		-263	-300	-296
Yield displacement	mm	6.5	7.8	7.9
Max. displacement	mm	13.0	54.5	15.9
		-13.3	-26.6	-15.9
Ductility ratio		2	3.4-7	2

On the other hand, the maximum displacements are considerably different for the three specimens. The load-displacement curves of the specimens are shown in Fig.6. The obtained ductility of specimen No.2 was similar to that of specimen No.0, which shows that CF Rope was not so effective with a small amount. However, when the amount of rope doubled (specimen No.1), the ductility ratio significantly increased. In specimen No.1, since the negative yield displacement was taken at the load equaled to the yield load in the positive direction (P_y), its value was different from the positive yield displacement.

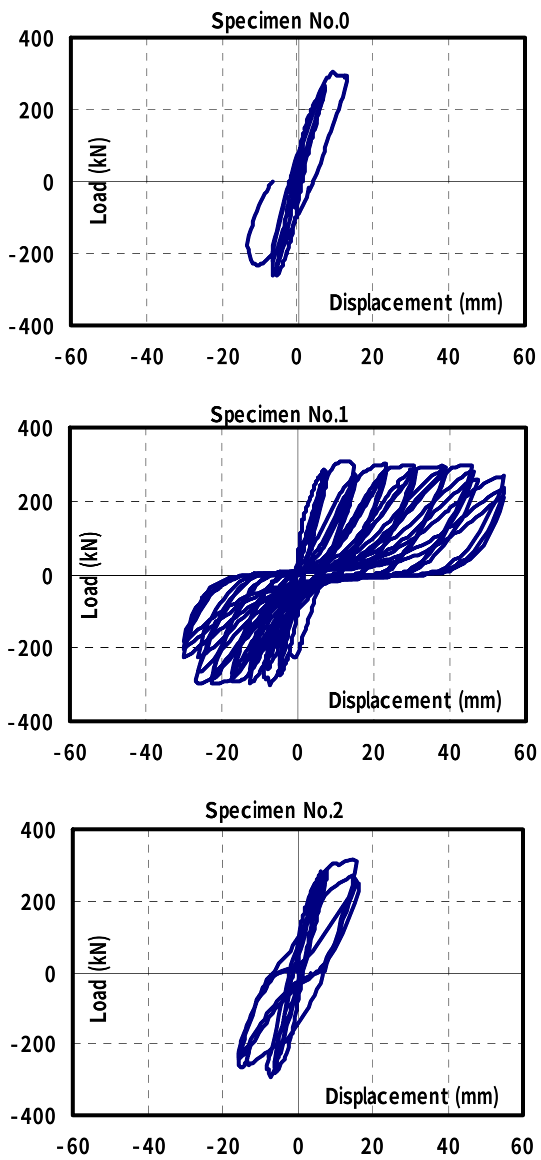

Fig.6 Load - displacement curves

(2) Development of strain of CF Rope

During the loading tests, the strain of CF Rope was measured by strain gauges attached directly to the rope surface.

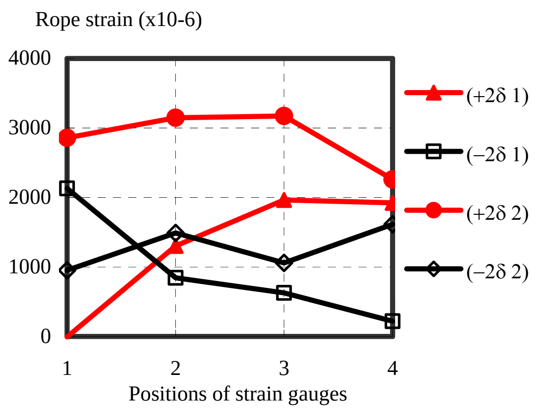

Fig.7 Distribution of CF Rope strain

Figure 7 shows the distribution of CF Rope strain during the second cycle of the loading test (±2δ). Positions of strain gauges on rope and crack pattern at this stage are shown in Fig.8.

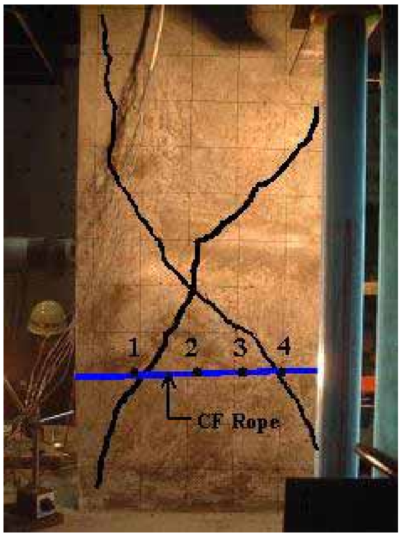

Fig.8 Positions of strain gauges and crack pattern at second cycle (No.1)

Let's focus on the first repetition of the second cycle (±2δ1). When the load changed its direction, causing different cracking patterns (Fig.8), the distributions of CF Rope strain were also different (Fig.7). The strain gauges closer to the main shear crack showed higher strain of rope, which means bonding between CF Rope and concrete jacket remained at this stage (±2δ1).

However, in the next repetition of this cycle (±2δ2), even with changing of load direction and crack patterns, the strain of CF Rope was almost equally distributed. This fact means that the bonding between CF Rope and concrete jacket was gradually lost with the delaminating of concrete jacket. This hypothesis was also suggested by examining the concrete jacket after the test.

(3) Failure modes

All specimens failed in shear mode with large diagonal cracks. The crack patterns of the specimens are shown in Fig.9. Specimen No.1 had more distributed cracks than specimen No.2. However, some observed cracks (not main shear cracks) were those in concrete jacket and did not correspond to those in original concrete column.

During the loading test, concrete jacket gradually lost bonding with the column concrete and rope and was removed from the column piece by piece. At failure, most part of jacket at loading surfaces lost bonding with column concrete and could easily be removed from the column.

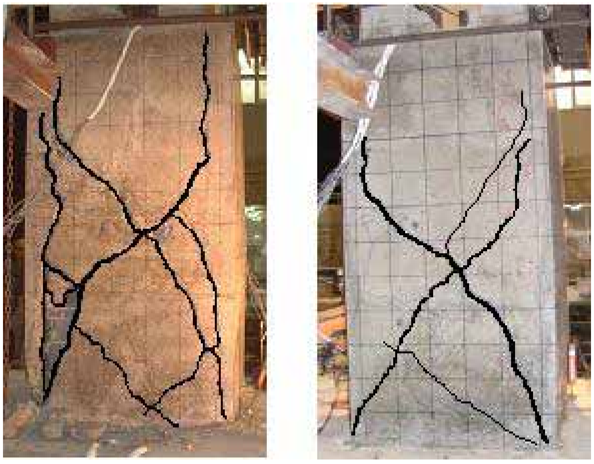

Fig.9 Crack patterns of specimen No.1 (Left) and specimen No.2 (Right)

The column concrete at the loading surfaces of specimen No.1 showed compressive failure of concrete at the final stage. CF Rope was not ruptured even at the failure of the member for both specimen No.1 and specimen No.2 (Fig.10).

Fig.10 Failure of specimen (No.1) – jacket removed, CF Rope not ruptured

5. COMPARISON BETWEEN RC COLUMNS RETROFITTED WITH CF ROPE AND THOSE WITH CF SHEET

In the previous research, the authors have carried out reversed cyclic loading tests for a series of RC column specimens retrofitted with CF Sheet [2]. In these specimens, CF Sheet was wrapped around the periphery of the column and was bonded to the concrete surface by epoxy resin. Structural dimensions and material strengths in the column specimens before retrofitting are common between the previous and the present study.

Figure 11 shows the comparison of reinforcing materials ratio (ρ_{cf}) of rope and sheet, taking into account their tensile strength (f_{cf}). The ratio ρ_{cf} is determined by Eq. 1 for the case of CF Rope and Eq. 2 for the case of CF Sheet.

$$\rho_{cfr} = 2A_r / (a.b) \quad (1)$$

where,

A_r : cross sectional area of CF Rope (mm^2)

a : spacing of CF Rope (mm) (in the case of double wound CF Rope, a is half of the single rope spacing)

b : width of column (mm)

$$\rho_{cfs} = 2t_s / b \quad (2)$$

where,

t_s : thickness of sheet (mm)

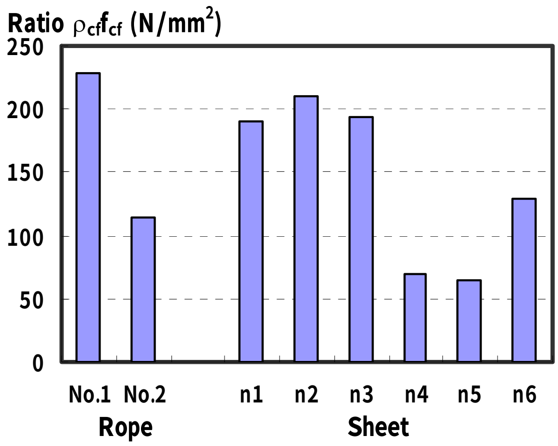

Fig.11 Ratio comparison between rope and sheet

Table 6 Test results of RC columns retrofitted with CF Sheet

Items	Unit	n1	n2	n3	n4	n5	n6
Type of sheet		Carbon	Aramid	Aramid	Aramid	Aramid	Aramid
Thickness of sheet	mm	0.111	0.193	0.169	0.064	0.056	0.113
Ratio of sheet	%	0.044	0.077	0.068	0.026	0.022	0.045
Maximum load	KN	306	298	300	294	297	294
		-307	-310	-315	-290	-287	-303
Maximum displacement	mm	45.7	48.1	73.7	15.4	20.7	44.0
		-45.7	-48.2	-176.0	-16.3	-21.2	-38.5
Ductility ratio		7	8	11	3	4	7

Test results of the specimens retrofitted with CF Sheet are summarized in Table 6. Similar to the case of CF Rope, ultimate capacity of the specimens is not influenced by CF Sheet wrapping, but ductility significantly depends on reinforcing ratio and properties of sheet [2]. It is the same for both CF Rope and CF Sheet that the larger amount of fiber, the greater the ductility.

Figure 12 shows crack patterns and debonding area of sheet in the typical specimens retrofitted with CF Sheet. The shaded areas are the area of debonding of CF Sheet at failure of the specimens. Again, it is observed in both cases of rope and sheet that specimens having more distributed cracks come up with larger deformation capability or ductility [2]. In the case of sheet, debonding area is also a key factor for ductility consideration [2].

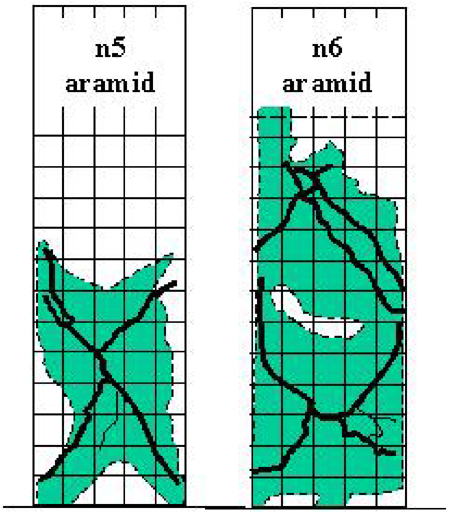

Fig.12 Typical crack patterns of RC columns retrofitted with CF Sheet

The difference between the case of CF Sheet and CF Rope lies in the fact that CF Sheet is bonded to column surfaces by epoxy resin, while CF Rope is covered with concrete jacket instead of epoxy resin.

In the case of CF Rope, bonding between rope and concrete was lost at an earlier stage than in the case of CF Sheet. Therefore, the strain of rope was equally distributed. In other words, there was no strain concentration. Thus, even with small ratio, CF Rope in this study was not ruptured at the column's failure.

On the other hand, in the case of CF Sheet, since bonding between sheet and concrete by epoxy resin is high, it makes the local strain of sheet great at the position of crack and causes the rupture of sheet along wide cracks at the failure stage [2].

6. CONCLUSIONS

(1) A seismic retrofitting method using CF Rope with concrete jacket was developed. It was experimentally verified that ductility of RC columns could be improved by this retrofitting method.
(2) Larger amount of CF Rope gives larger ductility of the column retrofitted.
(3) Bonding between CF Rope and concrete is gradually lost under reversed cyclic load. Therefore, CF Rope was not ruptured at the failure of column.

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