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A STUDY ON STRENGTHENING WITH CARBON FIBER FOR EARTHQUAKE-RESISTANT CAPACITY OF EXISTING REINFORCED CONCRETE COLUMNS

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SUMMARY

A method of increasing earthquake-resistant capacity of existing reinforced concrete columns by winding high-strength carbon fibers around column surfaces to add spiral hoops was researched and developed. As a result of experiments on the structural performance, it was found that earthquake-resistant capacity is improved by winding on of carbon fibers. And the relationship between carbon fiber quantity and earthquake-resistant capacity, the fact that substrate treatment is not essential, and that carbon fiber quantity can be converted to hoop quantity became known.

INTRODUCTION

The aseismic provisions in the Building Standards Law were revised as a result of the 1968 Tokachi-oki Earthquake. When enlarging or remodelling a building constructed before revision of the Standards, the current laws and regulations apply so that there will be cases when strengthening for earthquake-resistant capacity (Refs. 1,2) will be required. Meanwhile, in Japan, research on high-tech materials is being actively pursued. These high-tech materials include those high in durability and heat resistance, and those of high strengths and moduli of elasticity compared with conventional materials (Fig. 1). However, high-tech materials are generally expensive, and are not practical unless high added values exist in the methods of use.

Therefore, the authors contemplated making use of carbon fiber, a high-tech material, for the purpose of strengthening for earthquake-resistant capacity. In work for such strengthening, personnel costs are much more governing than material costs unlike in case of general construction work on the building, and it was judged that the use of carbon fibers would not be disadvantageous from the standpoint of cost. Experiments conducted to ascertain the structural performance of strengthening earthquake-resistant capacity with carbon fibers are described in this report.

STRENGTHENING WITH CARBON FIBER

By carbon fiber is meant fiber with carbon as the main constituent. With carbon fiber of HP grade, the minimum elements are of diameters 5 to 15 microns and are called monofilaments. Strands made by bunching 1,000 to 24,000 monofilaments are the units for practical use. The authors thought to increase transverse reinforcement by continuously winding strands of HP grade continuous-type carbon fibers on existing reinforced concrete columns as a new method of strengthening for earthquake-resistant capacity (Fig. 2). The following points are the merits of this method which uses carbon fibers; ie. (1) carbon fiber is flexible and can be made to contact the concrete surface tightly for a high degree of confinement; (2) confinement is of high degree because carbon fibers of high strength and high modulus of elasticity are used; (3) the carbon fibers are lightweight; and (4) rusting does not occur.

Plastic elongation of carbon fiber does not occur at all, but since plastic deformability is not generally expected of transverse reinforcement, there is no problem about the use itself of a brittle material as transverse reinforcement. Rather, the bond with concrete is of more importance. When there is no bond, stress concerntrations in carbon fibers near cracks in concrete are reduced for less likelihood of breaking, but the capacity to suppress cracking of concrete will be inferior. In order to control bonding properties, providing the concrete surface with substrate treatment can be considered.

EXPERIMENTATION PROGRAM

Variables The following were major parameters in this experiment.

(1) Transverse Reinforcement The carbon fiber quantity was made a parameter in order to deduce a quantitative relationship between carbon fiber quantity and earthquake-resistant capacity. Regarding conventional hoop reinforcement there is considerable accumulation of research work and even more data can be utilized if there were to be a correlation with winding on of carbon fiber. Therefore, specimens with only hoop reinforcement were prepared, and comparisons between hoop reinforcement and carbon fiber were made. It was further considered that carbon fiber quantity and hoop reinforcement quantity were mutually convertible.

$$p_f \sigma_{CF} \nu_{CF} = p_w \sigma_{wy} \qquad (1)$$

where, p_f: winding fiber ratio (defined in the same way as p_w)
p_w: transverse reinforcement ratio
σ_{CF}: tensile strength of carbon fiber
σ_{wy}: yield strength of hoop reinforcement
ν_{CF}: strength effectiveness factor of carbon fiber, taken to be 2/3

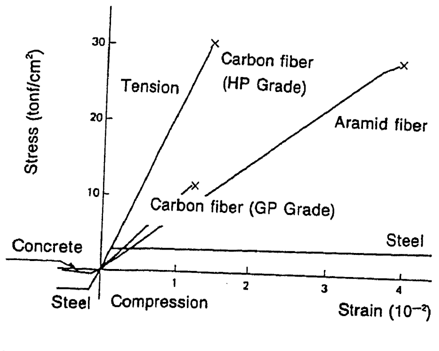


Fig.—1 Stress Strain Relationships of Several Materials

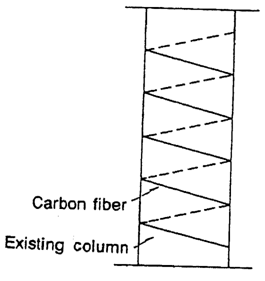


Fig.—2 CF Winding Method

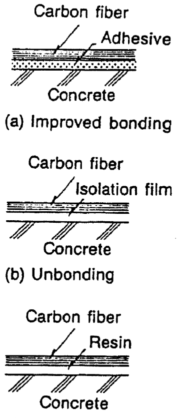


Fig.—3 Substrate Treatment

(2) Substrate Treatment With a column of rectangular cross section the only parts at which transmission of stress occurs between carbon fibers and concrete are the corners. Consequently, it may be expected that a condition of lost bond will occur even without substrate treatment. Therefore, two types were mainly studied as substrate treatments (Fig. 3); ie. (1) unbonding treatment, and (2) direct winding.

Specimens and Outline of Experiments The total number of specimens was ten with the scale of reduction 1/4. Details of the specimens are given in Table 1. In case of SS12EN, the carbon fiber quantity at midheight of the column was made 1/2 that at the ends (section at distance equal to column height from critical section). As for SS12BC, it was a specimen with bonding treatment only at corners

Table—1 Specimens

Specimen	Objective of Comparison	Transverse reinforcement ratio Pw (%)	Winding fiber ratio Pf (%)	Substrate treatment
SS00	Prototype	0.107	—	—
SS45S	CF and steel	0.46	0.058**	—
SS90S		0.93	0.15**	—
SS06	Prototype	0.107	0.06	Unbonding
SS12			0.12	
SS06N	Substrate treatment		0.06	Direct winding
SS12BC			0.12	Improved bonding only at corners
SS09N	Quantity of CF		0.09	Direct Winding
SS03N			0.03	
SS12EN			0.12 end 0.06 center	

* Index for increase in the quantity of transverse reinforcement

** These values, converted in to Pf calculated by equation (1), show increase in steel hoop from SS00.

Table—2 Materials

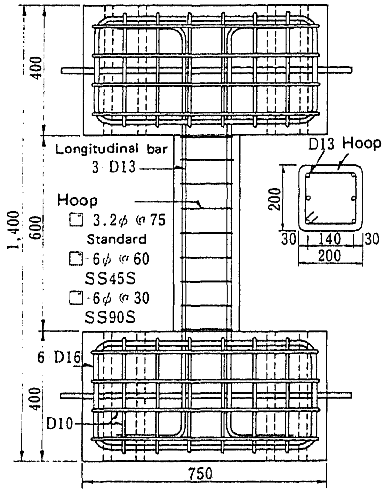
(a) Concrete			f_c =	279 kgf/cm²
(b) Steel bar				
	D13	deformed bar	σ_y =	4,190 kgf/cm²
		area = 0.71 cm²	σ_{max} =	6,110 kgf/cm²
	6ϕ	plain bar	σ_y =	3,580 kgf/cm²
		area = 0.28 cm²	σ_{max} =	4,790 kgf/cm²
	3.2ϕ	plain bar	σ_y =	3,280 kgf/cm²
		area = 0.080 cm²	σ_{max} =	4,180 kgf/cm²
(c) Carbon fiber				
		area = 0.23 mm²	σ_{max} =	29,300 kgf/cm²

f_c : compressive strength
σ_y : yield strength
σ_{max} : tensile maximum strength

Table—3 Experimental Results

Specimen	Maximum load (tonf)	Maximum load ratio	Ultimate Displacement (mm)	Maximum Strain of CF (10^{-6})	Failure Mode
SS 00	10.9	1.00	4 a	–	Shear
SS 45S	11.8	1.08	12 a	–	Bond
SS 90S	13.2	1.21	42 a	–	Flexure
SS 06	12.0	1.10	24 b	13,258	Bond + Breaking of CF
SS 12	13.2	1.21	50 <	10,028	Flexure
SS 06N	12.8	1.17	26 b	9,866	Breaking of CF after Flexural Yielding
SS 12BC	12.9	1.18	46 b	10,065	Breaking of CF in the flexural ultimate state
SS 09N	13.3	1.22	24 b	11,066	Breaking of CF after Flexural Yielding
SS 03N	12.1	1.11	15 b	10,135	Bond + Breaking of CF
SS 12EN	13.0	1.19	36 b	9,530	Breaking of CF in the flexural ultimate state

Remark: Ultimate Displacement
case a The displacement at which load deteriorates less than 80 percent of the maximum.
case b The displacement at which carbon fiber breaks and load decreases rapidly.



Longitudinal reinforcement ratio	0.95%
Transverse reinforcement ratio	0.107% (Standard specimen) 0.46% (S45S) 0.93% (S90S)
Axial stress	$F_c/6 = 46.6$kgf/cm²
Shear span ratio	1.5

Fig.—4 Specimen

of the column and with direct winding in the remaining portion. The reinforced concrete part of a specimen is shown in Fig. 4. All of the specimens were identical except for SS45S and SS90S which had increased hoop quantities. The cross sections were square, 20x20 cm, with the four corners beveled and rounded (radius 30 mm) in attempting to reduce stress concentrations on carbon fibers. Since columns of inferior earthquake-resistant capacity were the subjects of this strengthening method, reinforcement was arranged so that flexural failure would not occur in the specimen with no added strengthening (SS00).

A BRI-type loading apparatus was used for application of load and antisymmetric deformation was made to occur in the column. Cyclic displacements were forcibly induced with axial load maintained constant. The properties of the materials used are shown in Table 2. Carbon fiber strands were made solid with resin.

RESULTS OF EXPERIMENTS

The results of experiments are given in Table 3. Fig. 5 shows relationships between load and displacement, and the cracking patterns of concrete and residual carbon fibers at ends of experiments.

Failure Sequences In the specimen with no strengthening (SS00), a large shear crack occurred at translation angle of 1/150. At the same time load suddenly decreased and shear failure occurred.

When strengthening was done to some extent (SS45S, SS03N), bond cracks along longitudinal bars also grew. From translation angle of 1/50, crushing occurred along bond cracks, lowering of load was prominent and the mode became that of bond failure. Longitudinal reinforcement did not show flexural yielding.

When adequate strengthening was done (specimens other than the above three), flexural yielding occurred at translation angle of 1/80, crushing of concrete began at translation angle of 1/50, and the mode became that of flexural failure. However, with strengthening by carbon fibers, the carbon fibers broke at the final stage and loading capacity was rapidly lost except for SS12. Furthermore, bond cracks were seen in all specimens.

The specimens with direct winding, which had bond between carbon fibers and concrete at the initial stage, began to lose the bond at translation angle of 1/100.

Ultimate Displacement and Energy Dissipation The relationship between ultimate displacement and transverse reinforcement increase, and the relationship between hysteretic energy dissipation and transverse reinforcement increase are shown in Figs. 6 and 7, respectively.

(1) Carbon fiber quantity: Ultimate displacement and energy dissipation increased approximately linearly in accordance with carbon fiber quantity. This can be explained by the fact that confinement of concrete and allowance against breaking of carbon fiber were increased in proportion to increase in carbon fiber quantity.

On plotting the results of the specimens with only hoop reinforcement the points were on the same straight line. It is considered that conversion by Eq. (1) is approximately reasonable.

(2) Substrate treatment: The difference between unbonded specimens (SS06, SS12) and direct winding specimens (suffixed N or BC) were small. Even with direct winding, bond was lost ultimately between concrete and carbon fibers, which was

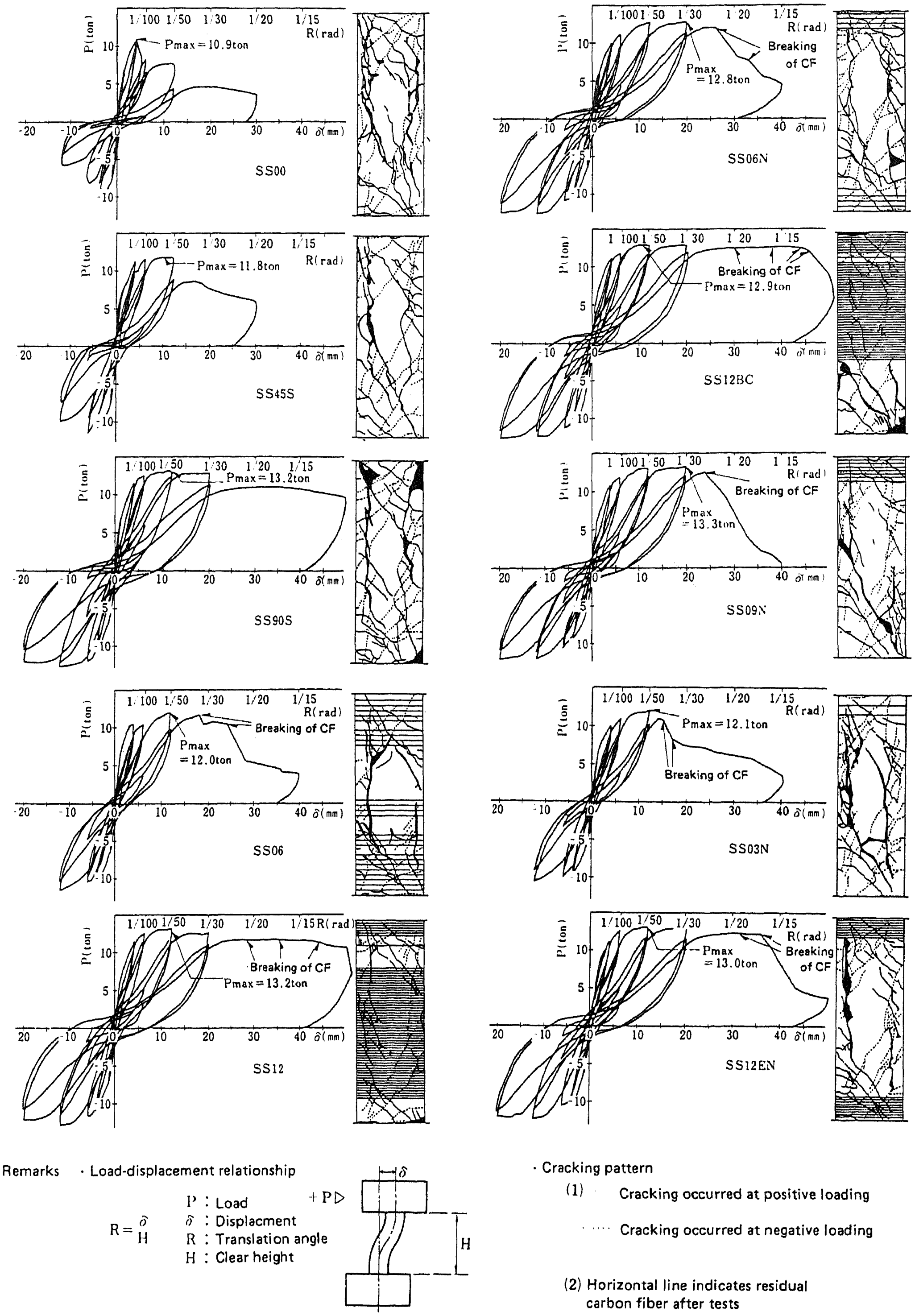


Fig.—5 Load Displacement Relation

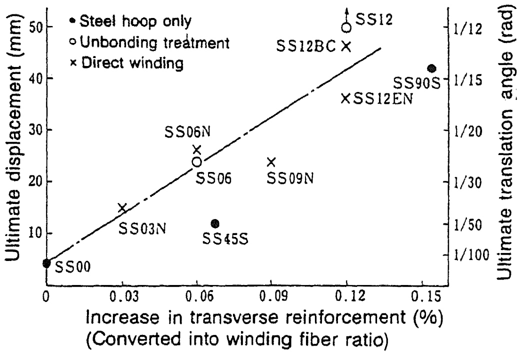


Fig.—6 Ultimate Displacement

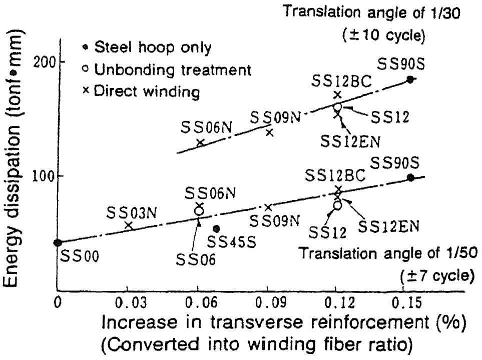


Fig.—7 Hysteretic Energy Dissipation

thought to be the reason why behaviors at large deformation such as ultimate displacement and energy dissipation became similar to those for unbonded specimens.

CONCLUSIONS

It was ascertained that winding on of carbon fiber has ample effect of strengthening earthquake-resistant capacity. And the following were found:

(1) Ultimate displacement and energy dissipation were increased approximately linearly accompanying increase in carbon fiber quantity.

(2) Earthquake-resistant capacities were not very much different on comparison of the substrate treatment method in which carbon fibers and concrete are not bonded and the method in which carbon fibers are wound directly on concrete, and

(3) When carbon fiber quantity is converted to steel hoop reinforcement quantity by effective strength ratio, the earthquake-resistant capacity of a carbon fiber-strengthened column can be correlated roughly with an ordinary reinforced concrete column having only hoop reinforcement.

ACKNOWLEDGEMENTS

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