論文 Application of Unresin Continuous Carbon Fibers as Flexural Reinforcement in Concrete Structure

Djamaluddin RUDY[*1] Yuichi KOBAYASHI[*2]
Takayuki NAGAHAMA[*3] Toshiaki OHTA[*4]

ABSTRACT: This study investigates the feasibility of using non-corroding unresin continuous carbon fibers as a substitute for steel reinforcement in concrete structures. In this paper, the flexural behavior of concrete beams reinforced by unresin continuous carbon fibers are introduced and the conclusion based on the experimental and analytical studies are presented. The effects of reinforcement ratio and compressive strength of concrete are investigated. The result indicates that the carbon fiber can be a good alternative for steel reinforcement in concrete beams with efficiency about 80%.

KEY WORD: unresin continuous carbon fiber, flexural behavior, reinforcement ratio.

1. INTRODUCTION

In recent years, there has been increasing concern about the durability of concrete structures, because of corrosion of the steel reinforcement, especially for concrete structures which has direct contact with natural weather environments such as bridge decks and parking garages. Corrosion by chloride ions of steel reinforcement embedded in concrete is recognized to be the main cause of concrete deterioration. In order to inhibit or eliminate steel corrosion in concrete structures, several techniques such as epoxy coated rebar, synthetic membranes, latex concrete, cathode protection, special paints, and sealant are developed (R.Masmoudi et.al 1996)[1]. However, their long-term efficiency is still questionable with regard to field experience.

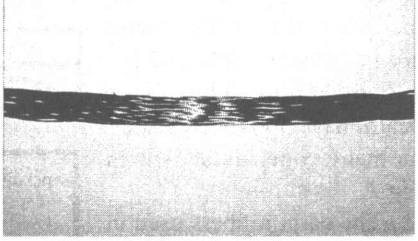


Figure 1 Unresin Carbon fiber

Currently, some non-corroding materials such as carbon fibers have been emerged as a promising material to replace the steel reinforcement in concrete structures. In particular, carbon fibers (CF) offer some

---

*1 Graduate Student, Graduate School of Eng., Kyushu University, M.Eng, Member of JCI
*2 Graduate Student, Graduate School of Eng., Kyushu University
*3 Graduate Student, Graduate School of Eng., Kyushu University, Dr.E., Member of JCI
*4 Professor, Graduate School of Eng., Kyushu University, Member of JCI

great potential for reinforcing the concrete structure under corrosive conditions. The advantages of carbon fibers include high tensile strength and stiffness to weight ratio, resistance to chemical attack and ease handling. Developing an advanced composite material to replace the steel reinforcement in the concrete structure has increase rapidly in last decade. This advanced material consists of strong fibers such as glass, carbon and aramid fibers, embedded in a resin matrix (K.S.McKay et.al 1993)[2]. Here, the carbon fiber without resin matrix (hereinafter called unresin continuous carbon fiber, Fig.1) is used as reinforcement for concrete beams. The motivation for using the unresin continuous carbon fiber is to utilize the extraordinary advantages such as higher tensile capacity than CFRP (carbon fiber reinforced plastic/resin) (JCSE)[3],(Y.Nukushina et.al 1989)[4], high tensile modulus, light weight, easy to tie on anchor, easy carrying and cutting, flexible like a rope, easily to be profiled, etc. Beside that, by using the unresin continuous carbon fiber as reinforcement materials, it seems possible to construct an automatically reinforcement arranger machine, to transport the arranged reinforcement in compact shape, to keep construction price and time down and moreover the construction industries possible to enter in the IT (Information Technology) era etc.

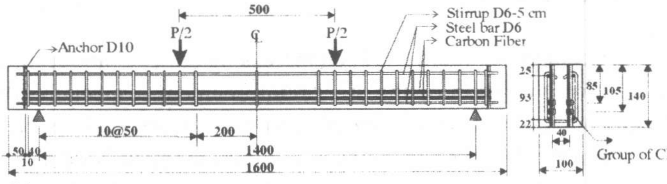
The experimental study of flexural behavior of concrete beam reinforced by unresin continuous carbon fiber with focus on flexural reinforcement is a good starting point for a feasibility study of application of unresin continuous carbon fiber as reinforcement in concrete structures. This study investigates the feasibility of using non-corroding unresin continuous carbon fibers as a substitute for steel flexural reinforcement in concrete structures, specially in concrete beam. The effects of reinforcement ratio and concrete strength are investigated.

2. EXPERIMENTAL STUDY

2.1 SPECIMENS AND TEST PROCEDURE

Flexural tests for two types of concrete beams reinforced by unresin continuous carbon fibers are carried out. The concrete strength of Type I and Type II are 35 MPa and 60 MPa, respectively. The simple supported beams have a span length of 1400 mm. The dimensions of concrete beams are 100 mm in width, and 140 mm in height. The tested beams have 500 mm constant moment zone, as shown in Fig.2.

The carbon fibers used in this study consist of 24 sub strands per one strand, and 3000 micro fibers per sub strand. This type has 3.53 GPa ultimate tensile strength, 230 GPa young modulus and



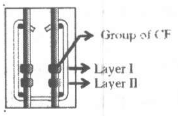
(a) SPECIMEN (b) CROSS SECTION

Figure 2 Dimension of test specimen

Table 1 Properties of unresin continuous carbon fibers

Type	E_{CF} (GPa)	f_t (GPa)	ε_u (%)	A (mm^2)	Density (g/cm^3)
24x3000	230	3.53	1.54	2.65	1.76

Table 2 Test specimens

Specimen Types		Concrete strength (MPa)	Strand per groups	Section area per groups (mm^2)	Reinf. ratio ρ (%)	Notes
I	A	35	8	21.2	0.89	
	B		10	26.5	1.12	
II	C	60	8	21.2	0.89	
	D		10	26.5	1.12	
	E1		12	31.8	1.34	
	E2		12	31.8	1.34	

density of 1.76 g/cm^3 with 2.65 mm^2 section area per strands (Table 1).

As shown in notes of Table 2, the carbon fiber group is divided in two layers that are layer I and layer II with same section area. Each layer consists of two groups. Because of the surface of carbon fiber is smooth, carbon fibers that embedded in concrete develop bond by adhesion between concrete and the carbon fiber, and by a small of friction. Both of these will quickly lost when the reinforcement is loaded in tension. Based on this reason and to keep the reinforcement in taut condition, the end anchor made from D10 steel bar is still used in this study (Fig.2). Another uncorrosive materials such as CFRP rod, ceramics, etc or another anchoring system will be applied as an end anchors in the next study. Needed area of carbon fibers is wound between two anchors at the both end of beam in the taut condition and tying the end of strand at the end anchor. The adhesive is used on the tying point of carbon fiber strand at end anchors to prevent a slip when reinforcement is loaded in tension. Here, the steel stirrup is still used as shear reinforcement to prevent a shear failure because of the present study just focus on the application of unresin continuous carbon fiber as flexural reinforcement.

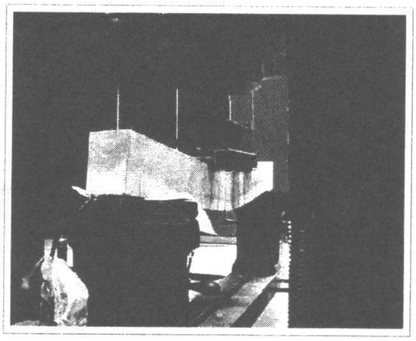


Figure 3 Specimen under test

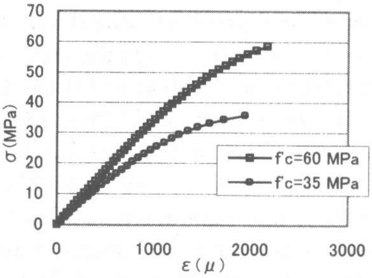


Figure 4 Stress-strain curve of cylinder test of concrete.

All of beams are loaded in four-point bending (Fig.2) that subjected to static load. Loading procedure is divided in two steps. Firstly, the applied load is used as a control until ultimate load. The load is applied gradually to the beam at a rate 1 kN per step by means of one hydraulic jack. And for the second step, the mid span deflection is used as a control. Load is given based on the mid span deflection rate that occurs until the end of testing. The figure of specimen under test is presented in Fig.3. The appeared cracks are also monitored at the end of each step so that the propagation of crack can be easily monitored.

The cylinder test result of both of concrete types are presented in Fig. 4 as a stress-strain relationship. The cylinder test results show that the concrete start to crush approximately 2000μ of compressive strain.

2.2 RESULTS AND DISCUSSION

The measured deflections of specimens Type I and Type II at mid span of beam are presented in Fig.5 and Fig.6, respectively. Generally, flexural behavior of concrete beam that reinforced with unresin continuous carbon fiber has the same behavior with concrete beam that reinforced with steel bar in which consists of linear part (elastic stage) and nonlinear part (plastic stage). The linear part of carbon fiber reinforced concretes is as same as the linear part of steel reinforced concrete beam. When the behavior enters in the nonlinear stage, the nonlinear behavior is little different with the nonlinear behavior of the steel reinforced concrete beam. The nonlinear stage of carbon fiber reinforced concrete beam consists of three parts, that are ascending part, descending part and a rather horizontal part, as shown in Fig.5 and Fig.6.

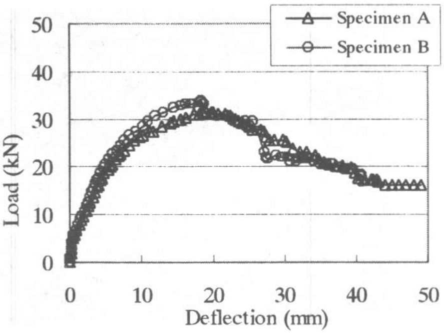


Figure 5 Load-Deflection curve for Type I

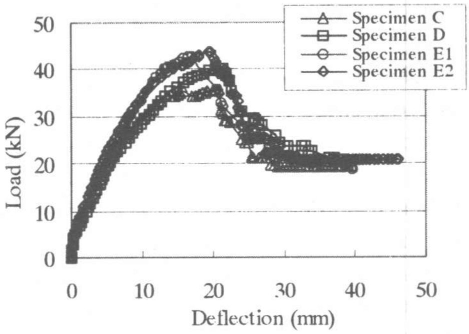


Figure 6 Load-Deflection curve for Type II

The horizontal part starts after descending part at load level approximately 50% of ultimate load, as can be observed through the load-deflection relationships (Fig.5 and Fig.6). The strain at uncracked stage is very small and stress distribution is essentially linear. The load-deflection for this stage is almost linear. When the stresses at the bottom of the beam reached the tensile strength of the concrete, cracking occurred. After cracking, the tensile force in the concrete is transferred to the carbon fiber. As a result, less of the concrete section is effective in resisting moments and the stiffness of the beam decreases. Thus the slope of the load-deflection diagram also decreases. The stress distribution of concrete is still close to linear at this stage. Once the ultimate compressive stress has occurred, the deflection increases with little increase in load. This stage, the upper side of concrete beam starts to fail due to crushing of the concrete at the top of the beam. Once the top of concrete beam has crushed, the load falls approximately 50% of ultimate load with little increase in deflection and then deflection still propagates at almost same load level until the end of test. Based on experimentally observation, the crushing starts around the position of applied load. The decreasing of load from peak load to horizontal part of load-deflection curve for Type I are 44.3%, 35.8%, for A and B, respectively and for Type II are 40.6%, 41.2%, 48.3%, 50.7% for C, D, E1 and E2, respectively. In this stage, the compressive stress in concrete is transferred to the remain cracked part of concrete that forms concrete blocks.

Table 3 shows that as the reinforcement ratio increases, the peak load increases about 7.6% for specimens with concrete strength 36.0 MPa (specimen A and B). This phenomenon is also found in specimens Type II that has higher concrete strength than Type I (specimen A and B) in which the peak load increases about 12.6% by increasing reinforcement ratio from 0.89 to 1.12 and increases 7.6 % by increasing reinforcement ratio from 1.12 to 1.34. Furthermore, the effect of concrete strength indicates that peak load increases about 13.7% by increasing concrete strength from 36.0 Mpa to 56.8 MPa for reinforcement ratio 0.89% and increases about 18.9% by increasing concrete strength from 36.0 Mpa to 51.2 MPa for reinforcement ratio 1.12%.

Table 3 Summary of experimental result

Spec. Type		f'c (MPa)	Reinf. ratio ρ (%)	Ultimate load (kN)			Efficiency of CF area (%)
				Exp	Calc	Efficiency (Exp/Calc)	
I	A	36.0	0.89	31.4	38.8	0.81	47
	B	36.0	1.12	33.8	41.2	0.82	48
II	C	56.8	0.89	35.7	48.7	0.73	38
	D	51.2	1.12	40.2	49.1	0.82	51
	E1	51.2	1.34	42.7	57.8	0.74	58
	E2	58.8	1.34	43.7	56.0	0.78	45
Average						0.78	47.8

By comparing the calculation based on the elastic beam theory ("Reinforced concrete" 1988)[5] and experimental results (Table 3), it can be noticed that the efficiency of concrete beam reinforced

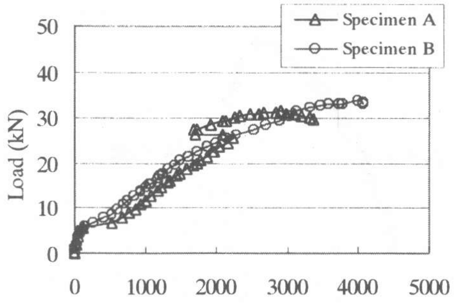


Figure 7 Load-CF Strain curve for Type I

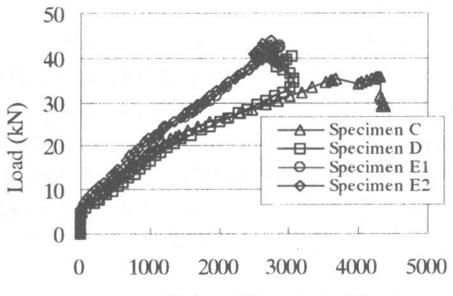


Figure 8 Load-CF Strain curve for Type II

by unresin continuous carbon fibers is about 78% (≈80%) where only 47.8% (≈50%) of unresin continuous carbon fiber reinforcement was effectively under stress when loading beams.

Furthermore, the carbon fiber strain for specimens Type I and Type II are presented in Fig.7 and Fig.8, respectively. And, Fig.9 is presented to show the crack propagating stage of specimen E2 as an illustration for crack propagating.

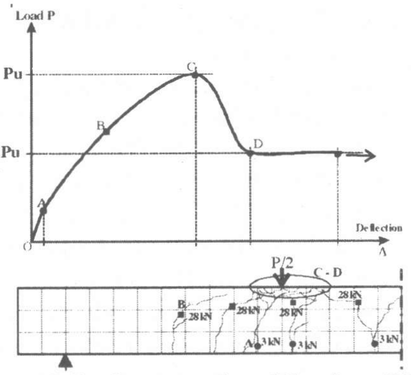


Figure 9 Crack propagating of Specimen E2

3. ANALYTICAL STUDY

3.1. FINITE ELEMENT MODEL

In this analytical modeling, two types of element are used to compose a modeling for concrete beam reinforced with unresin continuous carbon fiber. Those elements are 8-nodes plane stress element used to model the concrete and 3-nodes bar element to model a carbon fiber and steel. Because of existing of the end anchors and simplification purposes, the full bonding between carbon fiber and concrete is taken as an assumption to construct this analytical model. By existing of the end anchors, the relative slip between carbon fiber reinforcement and concrete is small. Nevertheless, the partial composite model where slip between carbon fiber and concrete possible to occur has been carried out based on the result of pull-out test (for predicting the spring stiffness of joint elements of model).

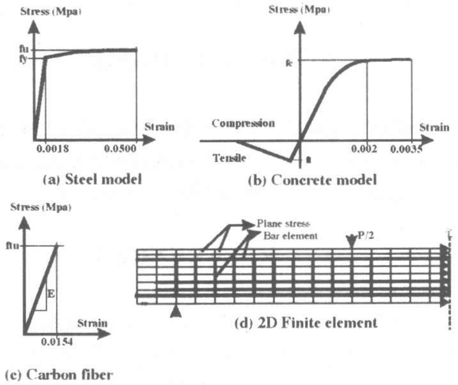


Figure 10 Material model and FEM model

Material model for concrete, steel and carbon fiber are presented in Fig.10. Due to the symmetrical nature of the problem, only half span of the beam is modeled (Fig.10d). The actual section area of carbon fiber that works effectively as reinforcement (based on the efficiency of carbon fiber section area presented in Table 3) is used as a section area of carbon fibers in analytical model by FEM.

3.2. RESULT

There is a good agreement between the FEM analytical and experimental results until ultimate load. The comparison between the analytical and the experimental result for load-deflection, load-upper side strain of concrete, and load-carbon fiber (CF) strain relationship are presented in Fig.11, Fig.12 and Fig.13, respectively.

4. CONCLUSION

According to the experimental and analytical study, the major conclusions of this study may be summarized as follows:

(1) Carbon fiber can be a good alternative for steel as flexural reinforcement in concrete beam with efficiency about 80%.

(2) Based on the calculation by elastic beam theory, the efficiency of carbon fibers that effectively works as flexural reinforcement in concrete beam is 47.8% (≈ 50%).

(3) The assumption that not all of the carbon fibers effectively work as reinforcement can be accepted and has verified by analytical study.

(4) The analytical model result by FEM has good agreement with experimental result.

ACKNOWLEDGMENTS

Sincere gratitude is expressed to Prof. Shin-ichi HINO for his valuable supervision, advice and encouragement in conducting this study.

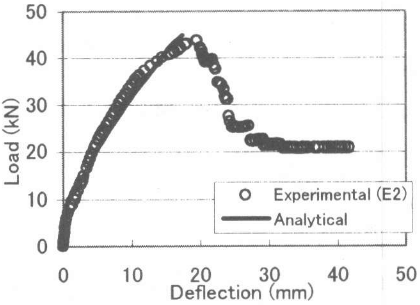


Figure 11 Load-Deflection

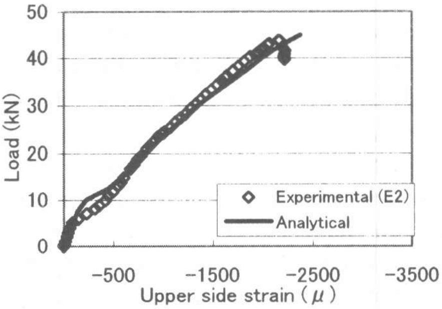


Figure 12 Load-Upper side strain of concrete

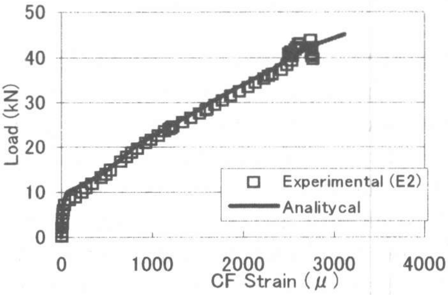


Figure 13 Load-CF Strain

REFERENCES

1. R.Masmoudi and et.al., " Cracking behavior of concrete beam reinforced with fiber reinforced plastic rebars," Can.J.Civ.Eng. 23, 1996,pp.1172-1197.
2. K.S. McKay and et.al, " Flexural behavior of concrete beams pretensioned with aramid fibre reinforced plastic tendons," Can.J.Civ.Eng. 20, 1993, pp.688-695
3. JSCE, "Provisional codes of JSCE for using continuous fiber-reinforced plastic to concrete structures," Concrete library, No.88, 1996, pp.317-323 (in Japanese).
4. Y.Nukushina and et.al, "On the Tensile Load to Elongation Response of Carbon Fiber Single Filament Sample," J.Compos.Mater., No.15, 1989, pp.210-221 (in Japanese).
5. James G.MacGregor, "Reinforced Concrete Mechanics and Design," Prentice Hall A Divison of Simon & Schuster, 1988, pp.91-105.