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"Composites'86: Recent Advances in Japan and the United States"
K. Kawata, S. Umekawa & A. Kobayashi, Ed., Proc. Japan-U.S. CCM-III, Tokyo, 1986.

Continuous Carbon Fiber Reinforced Cement

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Proceedings of the Third Japan—U.S.
Conference on Composite Materials
June 23—25, 1986, TOKYO JAPAN

JAPAN SOCIETY FOR COMPOSITE MATERIALS

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ABSTRACT

Continuous carbon fiber (C·CF) strand impregnated with epoxy resin was shaped into latticework and laminated with cement mortar. The surface of the resin-impregnated fiber was coated and treated in various ways. The flexural strength of mortar plank reinforced with impregnated carbon fiber strand which was coated with epoxy resin and fine sand was more than 350 kgf/cm^2 (34.3 MPa). In other words, stress-deformation curve is almost equal to that of plywood of the same thickness. Strain was dispersed into many hair cracks. This type of reinforcement proved to be effective to crack dispersion.

The flexural strength of mortar plank reinforced with impregnated carbon fiber strand which was coated with wet epoxy resin was almost satisfactory. However, it is not a practical way of fabrication, since the latticework is wet and difficult to handle. The flexural strength of mortar plank reinforced with impregnated carbon fiber strand which was coated with gypsum (Plaster of Paris) did not reach satisfactory level. As far as this type of reinforcement is concerned, water-soluble resin impregnation did not provide satisfactory effect.

In addition, two effective methods are suggested to suppress brittleness caused by sudden ultimate failure of carbon fiber. One is to make fibers slip at the interface with cement matrix. The other is partial and gradual failure of fiber.

The results are highly reproducible. And expected theoretical strength and deformation are easily achieved. Another advantage is that this type of reinforcement enables section design just like reinforced concrete design and ferro-cement products.

INTRODUCTION

In view of using high-strength new fibrous materials such as continuous carbon fiber (C·CF), glass fiber, etc., studies have been made to put these fibers together with inorganic matrix in order to develop fiber reinforced composites. So far, continuous glass fiber strands formed into reinforcing latticework with water-soluble emulsion was laminated with gypsum matrix to achieve almost equal flexural strength and deformation performance to that of plywood of the same thickness.

Carbon fiber is highly strong but thin. Therefore it is less rigid and small in surface area. It is strong in tension but weak in shear and accordingly susceptible to impact damage. Reinforcing cement matrix with C·CF should meet at least three conditions as follows:

- Fibers should be oriented in the desired position of the cross section.
- Fibers should be protected from damage by mechanical impact.
- Fibers should be sufficiently bonded with cement matrix.

Carbon fiber is heat-resistant and durable in highly alkaline environment of cement matrix. Therefore C·CFRC is good building material. However, sufficient performance is needed not only in strength but also deformation capability in order to gain much higher appreciation.

METHOD OF FABRICATION

Two methods are conceivable in order to orient C·CF strands in a desired position of the cross section.

1) Continuous fiber strand are stretched to be oriented in a mould and cement matrix is poured later.
2) Continuous fiber strands are glued into reinforcing latticework or mesh and laminated with cement mortar.

The first method is disadvantageous in that it is laborious to orient continuous fiber strands in a mould. Moreover, fiber orientation is susceptible to displacement on pouring cement matrix into a mould. The advantage of the second method is that it is easier to orient continuous fiber strand in a desired position of the cross section, though some technique is required in latticework fabrication.

Latticework fabrication with adhesive is also advantageous, since carbon fiber is coated and protected with hardened resin and mechanical damage can be prevented at the stage of fabrication. Thus, the second method was adopted where C·CF strand glued into latticework is laminated with cement matrix and formed into plank.

EXPERIMENTS TO ACHIEVE HIGH-STRENGTH

In order to reinforce cement matrix with C·CF, it is necessary to secure sufficient level of stress transfer between fiber and cement matrix. Various surface treatment were attempted on experimental latticework made of resin-impregnated C·CF. Plank-like specimens were obtained by laminating these latticeworks with cement matrix and their flexural performance was examined.

Specimens were prepared with materials listed in Table-1. First, carbon fiber strands were impregnated with resin and bundled into straight rod, which is about 1 mm in diameter. Three to ten rods run parallel to each other within the width of 4 cm. Fig. 1 shows an example of experimental latticework. Function of longitudinally-oriented fibers is to reinforce cement matrix. Laterally-oriented shorter fibers simply regulate the spacing of longitudinal fibers to be formed into latticework. Fiber latticeworks are treated in ten different ways in anticipation of better bond with cement matrix, namely:

a,f,g,i - mechanical bond by anchoring effect of sand fixed to fiber surface
b - adhesion of vinyl acetate resin
c - bond effect by hydration of cement
d,h - adhesion of epoxy resin
e - friction by expansive pressure of ettringite formation
j - adhesion of styrene butadiene rubber

Latticework and mortar were laminated in a mould to be shaped into specimen. Specimen is consistently 4 cm wide by 2 cm thick and either 32 or 16 cm long. Fiber content is either 0.135%, 0.270%, 0.316% or 0.395% by volume lengthwise. Cement matrix consists of mortar using river sand of 2.5 mm in diameter. Water:cement ratio is 40%, and sand:cement ratio is either 1.60 or 0.67. 28 days compressive strength is in the range of 316 and 529 kgf/cm^2. Flexural test was carried out on the specimens with either 13 or 26 cm span so that continuous fiber is in tension side of the cross section.

Table 2 shows flexural strength and failure mode. One or two large cracks propagated in specimens whose failure mode is represented by ●. Fiber is pulled out. These specimens has poor bond between fiber and cement matrix and their flexural strength is low. A couple of cracks propagated in the flexural tension side of specimens whose failure mode is represented by △. Here, a few pullouts were observed. These specimens are considered to have almost sufficient bond between fiber and cement matrix, and it has high flexural strength. Many small cracks dispersed in the flexural tension side of the specimen whose failure mode is represented by ○. No fiber pullout was observed.

Figure 4 shows the relation between C·CF content and flexural strength. Cement matrix has high compressive strength. Therefore neither shear nor compressive fracture was observed in the mortar matrix. Based on carbon fiber content, theoretical flexural strength in this case is represented by the straight line in Fig. 4 on the assumption of sufficient bond. ○, △ and ● in the diagram correspond with failure mode in Table 2. Specimen of sufficient bond ○ and almost sufficient bond △ achieved quite high strength, both of which made efficient use of high strength of carbon fiber. These are due to epoxy resin-impregnated carbon fiber latticework whose surface was again coated with either fine sand or wet epoxy resin. In the past experiment, vinyl acetate was remarkably effective to gypsum matrix, but not so effective to cement matrix.

Fig. 5 through 8 show the relation between flexural stress and mid-span deflection of the specimens. Notations a through j in these figures correspond with fiber surface treatment shown in Fig. 1.

Fig. 5 shows the result of flexural test of specimen with carbon fiber content of 0.135 vol %. Fig. 6 shows the same test result of 0.270 vol %. For both specimens, the relation between flexural stress and mid-span deflection is linear at an early stage of loading. However, flexural stress decreses rapidly once cracks occur in the matrix. Stress does not increase thereafter, but deflection alone increases remarkably. These specimens are excellent in deformation capability but poor in flexural stress or flexural strength. Judging from carbon fiber strength, it is estimated that flexural strength of 120 kgf/cm^2 is possible for the specimen of 0.135 vol %. Also flexural strength of 240 kgf/cm^2 is possible for the specimen of 0.270 vol %. Therefore high tensile-strength of fiber is not fully used here.

Fig. 7 shows the flexural test result of specimens with carbon fiber content of 0.316% by volume. The expected flexural strength of these specimens is 280 kgf/cm^2. Here again cracks occur at an early stage of loading just like the previous tests (Fig. 5 and 6). However, flexural strength increases remarkably with deflection. Specimen e has poor bond and flexural strength is low as compared with others. On the other hand, good bond was achieved between fiber and matrix for specimens f, g and h. Specimen f and g consist of epoxy resin-impregnated carbon fiber latticework coated with fine sand. Specimen h consist of epoxy resin-impregnated carbon fiber latticework coated with wet epoxy resin. For these three specimens carbon fiber failed at the maximum stress. These specimens make better use of high strength of carbon fiber and achieve the goal strength of 280 kgf/cm^2 with carbon fiber content of 0.316 vol %. For the reference, Fig. 7 also shows the flexural stress-deflection curve of 18 mm thick ordinary plywood almost equivalent to JAS 2 Class. It was revealed that C•CFRC planks represented by notation f, g and h have almost equal flexural strength and deflection to that of plywood. Therefore they are capable of resisting large flexural stress and deflection. However, two problems have yet to be overcome: namely poor rigidity like plywood and brittleness at the peak load due to sudden failure of carbon fiber which disables the specimen from carrying any more load.

Specimen f in Fig. 8 is to confirm the reproducibility of above-mentioned excellent flexural performance. This time carbon fiber content is 0.395% by volume and the goal strength of 350 kg/cm^2 is achieved. Specimen i is to confirm the fact that high flexural strength can not be expected with vinyl acetate at the stage of latticework fabrication, even though surface treatment is adequate. Surface of latticework is treated just like the specimen f, but flexural strength is lower. Specimen j is a trial of preventing sudden failure of carbon fiber by making it slip at interface with matrix, which accordingly prevents sudden failure of the specimen. Here the latticework is coated with SBR latex. Flexural strength is lower than 280 kgf/cm^2 which is a goal with fiber content of 0.318 vol %. However, deflection increases while maintaining flexural stress of about 200 kgf/cm^2. It is suggested that this is one of the practical methods of improving deformation capability.

4. EXPERIMENTS TO IMPROVE STRENGTH AND DEFORMATION CAPABILITY

It was revealed that high flexural strength composite can be obtained by C•CFRC. However, poor rigidity and brittleness must be overcome, which have already been mentioned. Rigidity can be improved by adding more carbon fiber. On the other hand, toughness can be realized by three methods are follows.

1) Yield of compressive side of cement matrix
   Effectiveness of this method have already been proven by experiments.(1) For practical purposes, some of the problems must be solved, namely mix proportion of cement matrix, cure after casting, long-term strength change, etc.

2) Slip at interface between fiber and matrix
This has been shown by specimen j in Fig. 6. In this method, SBR has been confirmed to be an effective way of treating carbon fiber latticework.

3) Stepwise failure of continuous fiber
More than two fibers of different strength, modulus of elasticity and elongation are properly oriented and positioned in the cross section of the matrix so that they fail one by one. Combination of carbon fibers of different strength and modulus of elasticity is effective as well as combination of carbon fiber and other fibrous materials. In this method, it is important to design the position of fiber orientation properly in the cross section. For example, even if one type of fiber is used alone, it is possible to make outer fibers fail first and inner ones later.

Here experiments are carried out on the third method, ie. stepwise failure method as mentioned above. Two different carbon fibers described in Table 3 are used. They are positioned in flexural tension zone of the cross section as shown in Fig. 9. As shown in Fig. 10, it was designed so that fiber L with smaller elongation fail first and fiber H with larger elongation fail next. Four types of specimens shown in Table 4 are fabricated whose goal flexural stress is about 200 kgf/cm^2. Reinforcing latticework is treated just like the specimen f in Fig. 2. Method of fabrication and flexural test is just like the one that has already been described.

In Fig. 11, observed results (solid line) are compared with theoretical ones (dotted line). According to the theory, cracks occur in the flexural tension side of the matrix first at an early stage of loading. Then flexural stress drops many times whenever carbon fiber fails partially while deflection constantly increases. In this experiment, specimen T03 and T04 are typical of this phenomenon. It is worthy to examine this type of method in order to prevent sudden failure of C·CF and improve both strength and toughness of C·CFRC products.

SUMMARY

It is possible to control flexural strength of C·CFRC plank by fiber content which is made of resin-impregnated carbon fiber latticework with adequate treatment. Mortar specimen reinforced with carbon fiber in one side by 0.316 vol % proved to have equal strength and deformation capability of plywood of the same thickness.

Moreover two effective methods are suggested to suppress brittleness caused by sudden ultimate failure of carbon fiber. One is to make fibers slip at the interface with cement matrix. The other is partial and gradual failure of fiber.

REFERENCE

(1) Kishitani, K. and Hirai, T.,
"Effective use of adhesive for continuous glass fiber reinforced cement"
Proceedings of the 4th International Conference on Composite Materials, ICCM-IV, 1982, JAPAN

Table 1. List of materials

Carbon fiber	About 1000 filaments are bundled into strand. Pitch-based carbon fiber Cross-sectional area: about 4.51×10^{-4} cm^2 Tensile strength: 198 kgf/mm^2
Epoxy resin	Commercially available, Setting time and viscosity are adjusted according to the purpose.
Vinyl acetate resin	Commercially available
SBR latex	
Sand	River sand 0.6 mm mesh on, 1.2 mm mesh through
Cement	Ordinary Portland cement Commercially available

Table 2. Result of flexural test

Specimen No.	Carbon fiber content (vol %)	Surface treatment	Flexural strength (kgf/cm^2)	Failure mode
121	0.135	a	74.6	●
122			72.4	●
123		b	80.1	●
124			76.5	●
125		c	74.0	●
126			76.3	●
127		d	86.9	●
128			98.8	●
129	0.270	a	70.2	●
130			75.4	●
131		b	135.2	●
132			123.9	●
133		c	90.1	●
134			77.8	●
135		d	106.6	●
136			107.7	●
203	0.316	e	191.8	●
204			199.0	●
205		f	342.7	○
206		g	282.8	○
207		h	260.7	△
208			318.0	△
303	0.395	i	164.7	●
304			192.7	●
305	0.316	j	206.4	●
306			199.0	●
307	0.395	f	330.3	○
308			382.1	○

○ Many small cracks in flexural tension side, no fiber pullout.

△ A few cracks in flexural tension side, a few fiber pullout.

● Concentrated cracks in flexural tension side, mostly fiber pullout.

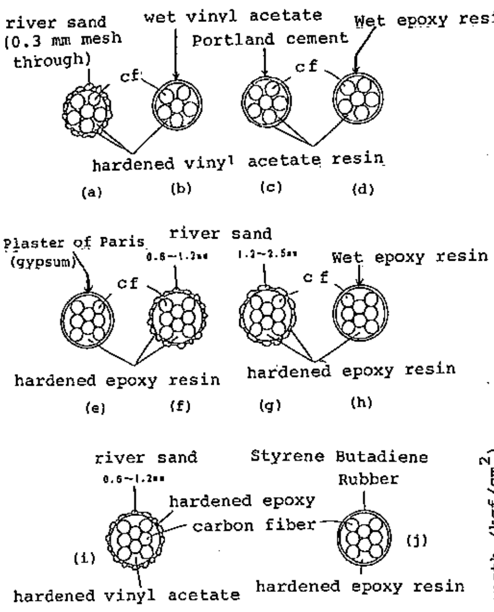


Fig. 2
Schematic cross section of CFRP strand

Fig. 1 Resin-impregnated carbon fiber latticework

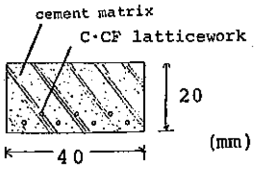
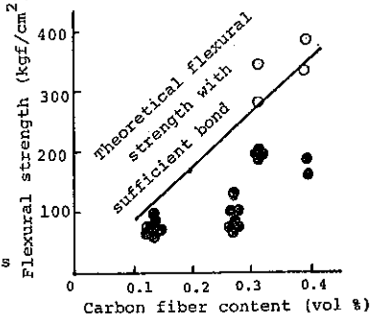


Fig. 3 Cross section of specimen

Fig. 4 Theoretical values vs. test results →



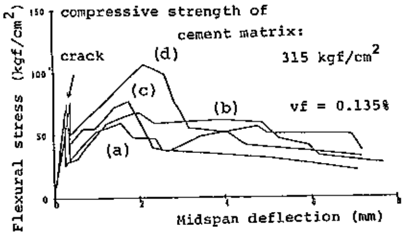


Fig. 5 Span: 13cm

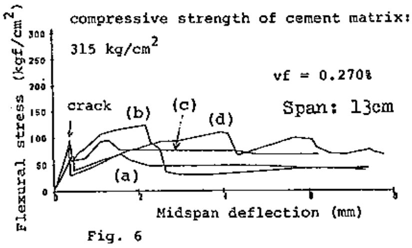


Fig. 6

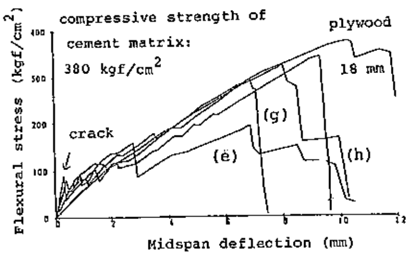
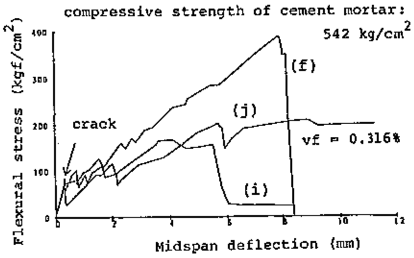


Fig. 7 vf = 0.316% Span:26cm



Span: 26cm

Fig. 8 vf = 0.395%

Table 3. List of pitch-based carbon fiber

Type of carbon fiber	Elongation (%)	Tensile strength (kgf/cm^2)	Modulus of elasticity (x 10^4 kgf/cm^2)
Fiber H	0.84	11,700	139
Fiber L	0.43	17,000	397

Table 4. Data of specimen

Specimen No.	Cross-sectional area of carbon fiber (mm^2)				Carbon fiber content (vol %)
	Inner layer		Outer layer		
	Fiber L	Fiber H	Fiber L	Fiber H	
T01	0.456	0.746	0.304	2.984	0.561
T02	0.304	1.119	0.152	1.492	0.383
T03	0.912	3.357	0.152	1.492	0.739
T04	0.608	2.238	0.152	1.492	0.561

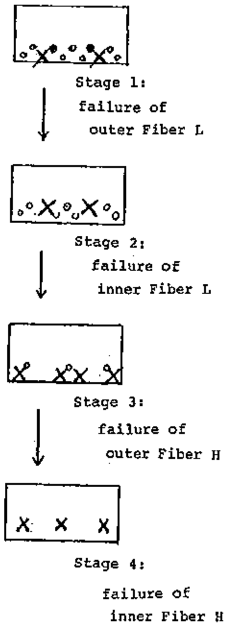


Fig. 10

Sequential failure of carbon fiber

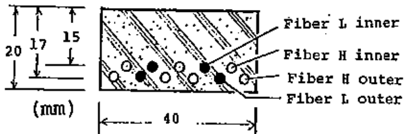


Fig. 9 Schematic cross section of specimen

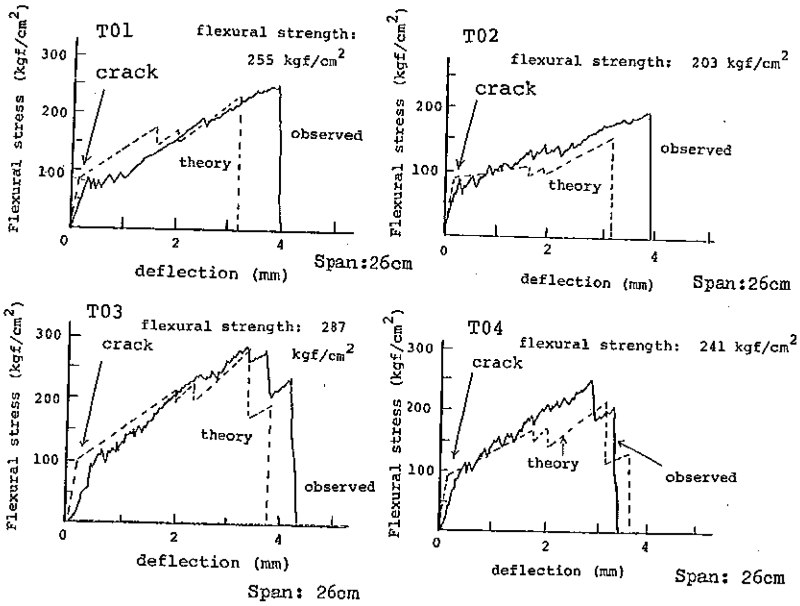


Fig. 11 Theoretical values vs test results