*- Technical Paper -*

# EXPERIMENTAL STUDY ON SHEAR BEHAVIOR OF CONCRETE BEAMS REINFORCED WITH CONTINUOUS FIBER ROPE

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ABSTRACT

A new type of continuous fiber material made in the form of rope is used as shear reinforcement for reinforced concrete beams. Continuous Fiber Rope (CF Rope) is enough flexible to be easily arranged in structural members by hand and is considered to be used without epoxy resin. A series of three beams with CF Rope as shear reinforcement were under bending shear tests. The effectiveness of CF Rope embedded in concrete was experimentally verified.

Keywords: continuous fiber rope, shear reinforcement, tensile test, concrete bonding

## 1. INTRODUCTION

Continuous fiber materials in many different types such as rods, grids, sheets, etc. have been widely used in concrete structures for their obvious advantages, namely high strength, high durability, and lightweight. In this study, a new type of continuous fiber material made in the form of rope, hereafter Continuous Fiber Rope (CF Rope), has been investigated. CF Rope is enough flexible to be easily arranged in structural members by hand and apart from other FRP materials for concrete so far, it is considered to be used without epoxy resin.

First, material tests were carried out to determine the mechanical properties of CF Rope. These properties were then used in designing the beam specimens for the shear test. The specimen series consisted of three beams with identical dimensions and longitudinal reinforcement, but different types of shear reinforcement.

Through the experiments, the failure behaviors of the beams were discussed and the shear strengthening effectiveness of CF Rope was evaluated. Experimental results are also compared with calculations in accordance with the JSCE design equations for continuous fiber materials.

## 2. PROPERTIES OF CONTINUOUS FIBER ROPE

### 2.1 Preparation of Test Pieces

The CF Rope (Fig.1) was made of aramid fiber. It is composed of eight bundles of fibers, each have 6000 filaments. One single filament has density of 1.44 g/cm$^3$ and weight per unit length of 1.5 denier.

Similar to other types of continuous fiber materials such as rods and sheets, the conventional friction grips used for steel rebars cannot be applied to CF Rope in tensile test. A special gripping system is used to transmit loads from the testing machine to the test piece. The gripping system consisted of steel tubes filled with expansive grout (Fig.2). The section of CF Rope inside the anchoring section was strengthening by FRP epoxy to

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prevent the rupture of rope inside the anchoring section.

Fig.1 Continuous fiber rope

After three days of curing, the pressure of expansive grout reached its maximum value and became stable and the test pieces were ready to be tested.

## 2.2 Results of Tensile Tests

The test pieces were tested using universal testing machine. Strain gauges were attached to the center of the test section of approximately 450 mm long through a layer of epoxy spread on the surface of the rope to measure strain of the test piece. The loading rate of the tensile tests was approximately 1.5 KN/min. Test setup is shown in Fig.2.

Fig.2 Tensile test of CF Rope

A total number of 15 test pieces were tested and the results are presented in Table 1. For calculation of Table 1, nominal cross sectional area of CF Rope is taken as 5.56 $mm^2$, which is determined from the properties of one single filament.

Table 1 Tensile Properties of CF Rope

| Tensile capacity (KN) | Tensile strength ($N/mm^2$) | Ultimate strain (%) | Young's modulus ($N/mm^2$) |
|---|---|---|---|
| 11.5 | 2070 | 2.2 | 94400 |

# 3. LOADING TEST OF BEAM SPECIMENS

## 3.1 Specimens Preparation

A total number of three specimens of the same dimensions and longitudinal reinforcement were produced. The specimens had different types of shear reinforcement of the left shear span namely no shear reinforcement, steel shear reinforcement (D10@150) and CF Rope shear reinforcement (CFR@150). For all beams, the stirrups in the right shear span (D10@100) were designed to have higher shear capacity than that of the left shear span in order to obtain a shear failure on the left side. Details of the beam specimens are presented in Fig.3.

For specimen No.3, the arrangement of CF Rope was as follows: CF Rope was fixed at one end by epoxy resin and simply rolled by hand around the longitudinal reinforcement and then fixed at the other end as shown in Fig.4.

In order for CF Rope to be unmovable, it was rolled at its shortest length. Therefore, the angle between CF Rope and the member axis can be determined by Eq. 1 as illustrated in Fig.5.

$$tan\,\alpha = \frac{2(b+h)-8v}{s} \qquad (1)$$

where,

$\alpha$ : angle between CF Rope stirrup and member axis

$b,h$ : width and height of beam

$v$ : thickness of concrete cover

$s$ : spacing of CF Rope stirrup in member axis direction

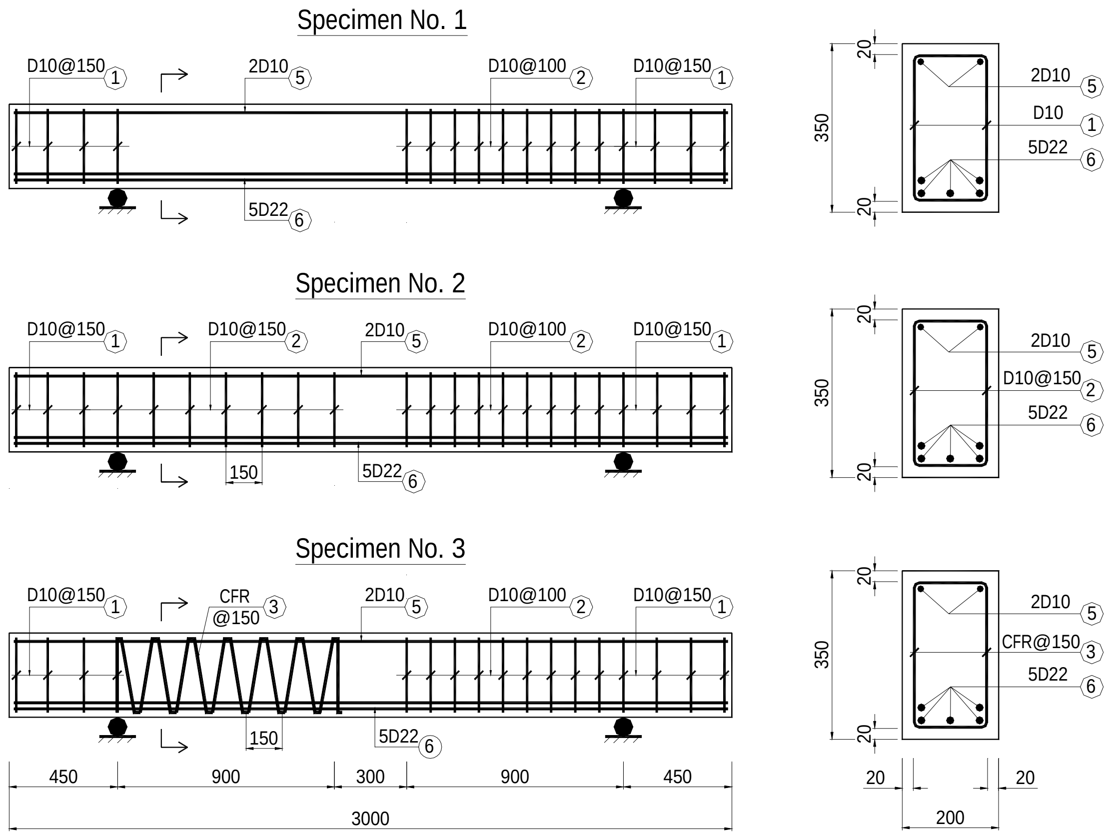


Fig.3 Details of specimens

Fig.4 Arrangement of CF Rope

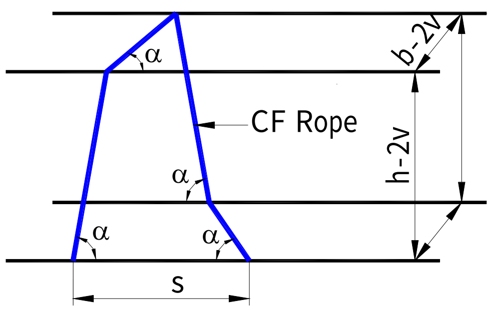


Fig.5 Angle of CF Rope

Further details of the specimens can be seen in Table 2 and Table 3.

Table 2 Specimens details

| Beam No | $f'_c$ (N/mm$^2$) | $a/d$ | Stirrups of left span Quantity | Material |
|---|---|---|---|---|
| 1 | | | No stirrup | |
| 2 | 46.7 | 3.1 | D10@150 | Steel |
| 3 | | | CFR@150 | Aramid |

($f'_c$: compressive strength of concrete; $a/d$: shear span effective depth ratio)

Table 3 Properties of reinforcement

| Material | Diameter (mm) | Area (mm$^2$) | Tensile strength (N/mm$^2$) |
|---|---|---|---|
| Steel D22 | 22.2 | 387.1 | 703.5 |
| Steel D10 | 9.53 | 71.33 | 363.7 |
| CF Rope | 2.66 | 5.56 | 2070 |

## 3.2 Test Setup

All beam specimens were simply supported and loaded with two-point load set-up. Beam displacement was measured at the two loading points, the center of the beams and the two supports by transducers. Concrete strains at tensile and compressive zones of the beams were measured by attached strain gauges. Strain gauges were also glued to the shear reinforcement of the left shear span of the beams to measure distribution of stirrup strain. Crack width and shear displacement of the main shear cracks was measured by clip gauge attached to the cracks after unloading the specimens. Test setup is shown in Fig.6.

Fig.6 Test setup of loading test

### 3.3 Test Results and Discussions

The load displacement curves of the specimens are shown in Fig.7.

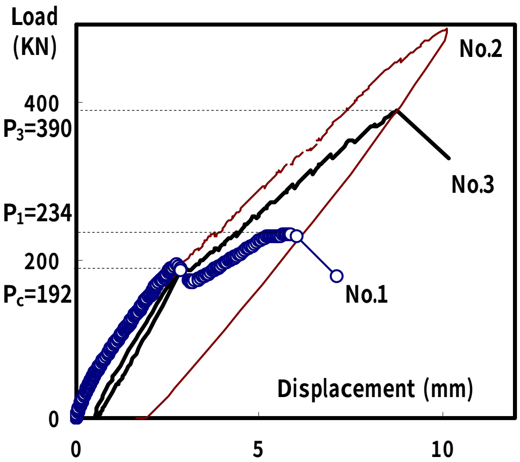


Fig.7 Load displacement curves of specimens

All beam specimens failed in shear mode, except specimen No.2, which did not fail as its shear capacity that was higher than the capacity of the jack used in the loading tests. For specimen No.1 and No.3, the measured strains at compressive zones of the beams at failure were much less than the ultimate strain of concrete ($\varepsilon'_u$=0.0035); these specimens failed in shear tension failure. Specimen No.3 failed with the rupture of one of the CF Rope stirrups.

The crack patterns at failure of specimen No.1 and No.3 were shown in Fig. 8. The crack patterns of the two specimens were similar with one main shear crack at the angle of approximately 28$^o$.

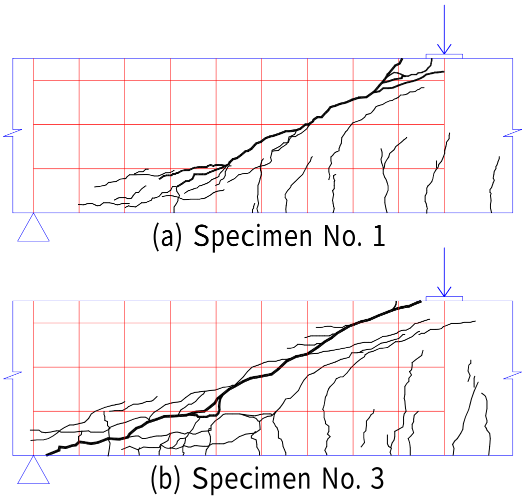


Fig.8 Crack patterns of specimens

At approximately the same load ($P_c$=192 KN), in specimen No.1 and No.3 the main shear crack appeared. Figure 9 shows the development of the strains at different points on one CF Rope stirrup on one side of specimen No.3.

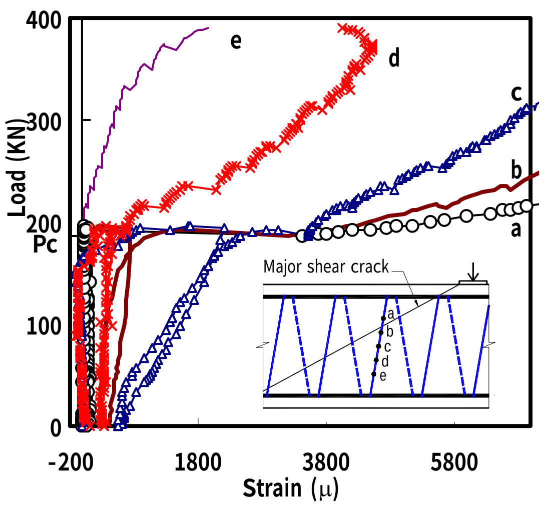


Fig.9 Development of CF Rope stirrup strains in specimen No.3

At shear cracking load $P_c$, the stirrup strains significantly increased while the load remained constant. This phenomenon is different from what was observed in FRP rods stirrup in concrete beams where load-strain curves had no horizontal parts [1].

After shear cracking load $P_c$, the strain at *a* and *b* positions increased rapidly even when the load did not increase and were approximately the same in value, while the strain at *c*, *d* and *e* positions increased slowly and were different from each other (Fig.10).

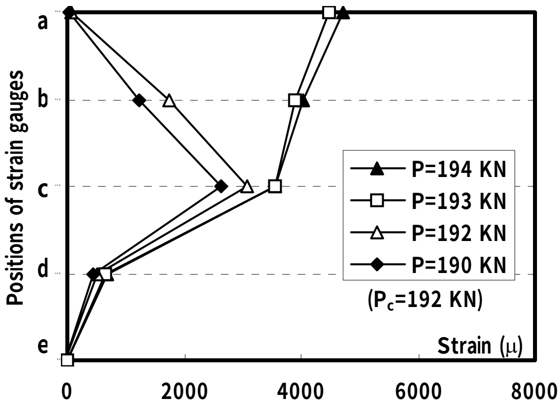


Fig.10 CF Rope stirrup strain distribution before and after major shear crack

That means, at the small area around the major shear crack (*a* and *b*), bonding between CF Rope and concrete was lost, while in other parts of the stirrup, bonding remained. This characteristic is similar to that of externally bonded continuous fiber sheet retrofitting reinforced concrete beams. In case of continuous fiber sheets, sheets were delaminated upward and downward from the major shear crack [4].

For specimen No.3, the directions of CF Rope stirrups on two sides of beam were different. Therefore, the angle between the CF Rope stirrups and the main shear crack were different. As a result, the stirrup strains on two sides of beam were not symmetrical. This effect will, however, become negligible when stirrup spacing becomes small (see Eq. 1).

## 4. SHEAR CONTRIBUTION OF CONTINUOUS FIBER ROPE STIRRUPS

For specimen No.3, the total shear capacity of specimen $V_{u3,exp}$ can be determined as the sum of the shear contribution of concrete $V_{c,exp}$ and that of CF Rope stirrup $V_{cfr,exp}$. As all the specimens had the same dimensions and longitudinal reinforcement, it can be assumed that the shear contribution of concrete $V_{c,exp}$ is the same as the ultimate shear capacity of the reference beam No.1, $V_{u1,exp}$. Therefore, the contribution of CF Rope stirrup in specimen No.3 can be evaluated by Eq. 2.

$$V_{cfr,exp} = V_{u3,exp} - V_{u1,exp} = P_3/2 - P_1/2 \quad (2)$$

where,

$P_1, P_3$ : maximum loads observed in specimen No.1 and No.3 (Fig.7)

Assuming the ideal case that all the CF Rope stirrups crossing the major shear crack of specimen No.3 reached its maximum tensile capacity obtained by tensile test at the failure of the beam, then the shear contribution of CF Rope stirrup would reach its idealized maximum value. This maximum contribution $V_{cfr,max}$, which is determined by Eq. 3, can be used to evaluate the effectiveness of using CF Rope stirrup by comparing with $V_{cfr,exp}$.

$$V_{cfr,max} = (n_1 + n_2) T_u \sin\alpha \quad (3)$$

where,

$n_1, n_2$ : number of CF Rope stirrup crossing major shear crack on two sides of specimen

$T_u$ : tensile capacity of CF Rope

The shear contribution of CF Rope stirrups can also be calculated using the design equation for continuous fiber reinforcing materials recommended by JSCE [6] as follows:

$$V_{cfr,cal} = A_w E_w \varepsilon_{fw} (\sin\alpha_s + \cos\alpha_s) z / s_s \quad (4)$$

where,

$A_w$ : total cross-sectional area of stirrups in section $s_s$

$\varepsilon_{fw}$ : stirrup strain in ultimate limit state

$$\varepsilon_{fw} = \sqrt{f'_{mc} \frac{p_w E_{fu}}{p_{web} E_w}} \times 10^{-4} \quad (5)$$

$E_w, E_{fu}$: Young's modulus of stirrup and tensile reinforcement, respectively

$p_{web} = A_w /(b.s_s)$

$p_w = A_f /(b.d)$

$A_f$ : cross-sectional area of tensile reinforcement

$$f'_{mc} = \left(\frac{h}{0.3}\right)^{-1/10} \times f'_c \quad (\text{N/mm}^2) \quad (6)$$

$h$ : member depth (m)

$\alpha_s$ : angle formed by stirrup and member axis

$s_s$ : spacing of stirrup

$z$ : distance from point of action of compressive stress resultant force

All values of $V_{cfr}$ in calculation and experiment are presented in Table 4.

Table 4 Shear contribution of CF Rope stirrup in specimen No.3

| $V_{cfr,cal}$ (KN) (1) | $V_{cfr,max}$ (KN) (2) | $V_{cfr,exp}$ (KN) (3) | (3)/(1) (4) | (3)/(2) (5) |
|---|---|---|---|---|
| 16.3 | 90.6 | 78.0 | 4.79 | 0.86 |

The experimental value of $V_{cfr}$ was significantly higher than the calculation value and close to the maximum one. It has been experimentally verified that CF Rope can be used effectively as shear reinforcement in reinforced concrete beams.

## 5. CONCLUSIONS

The tests of the series of specimens have experimentally confirmed that continuous fiber rope embedded in concrete can be used effectively as shear reinforcement for concrete beams. The shear strengthening effectiveness increases with the decrease of shear reinforcement spacing. Further experimental work is required for developing quantitative prediction methods for shear contribution of continuous fiber rope stirrups.

## ACKNOWLEDGEMENT

The authors would like to acknowledge Mr. Yuji Tasaka, graduate student of Nagaoka University of Technology, for his valuable assistance in carrying out the experimental works.

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