- Technical Paper -

EXPERIMENTAL STUDY ON SHEAR BEHAVIOR OF RC BEAMS JACKETED BY FLAX FIBER SHEET

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ABSTRACT

Flax is planted in rather cold climate for clothing and food, and can be made into nature fiber. The cost of flax fiber sheet is significantly less than conventional Fiber Reinforced Polymer (FRP) sheet. Flax fabric contains flax fibers in two orthogonal directions (warp and weft directions). In this study, beam test for six rectangular beam specimens with FRP sheet and one control specimen are conducted. As results, it is verified that flax fiber strengthening is effective for enhancement of shear behavior. In addition, the result of strengthening beams with flax fibers is discussed by comparing it with the case of beams strengthened with PET fibers.

Keywords: flax fiber, FRP jacketing, shear strengthening, coupon test, beam test

1. INTRODUCTION

Several Reinforced concrete (RC) structure without properly designed for shear reinforcement usually collapse catastrophically in shear under severe loading. In recent years, Fiber Reinforced Polymer (FRP) sheets have become increasingly in use for shear strengthening RC structures owing to their high stiffness, strength-to-weight ratios and design flexibility [1]. Conventional FRPs such as Carbon Fiber Reinforced Polymers (CFRP) and Aramid Fiber Reinforced Polymers (AFRP) are effective in enhancing shear strength, but their applications in structures is limited mainly by their high initial cost and relatively high environmental impact [2]. Instead of those synthetic FRPs, use of natural FRP (NFRP) such as flax FRP has gained popularity in engineering applications since they are more cost effective and environmental friendly while maintaining high mechanical properties comparable to those of Glass Fiber Reinforced Polymers (GFRP) used as reinforcement [3]. Although flax FRP can be applied in composite structures, its structural performance for strengthening RC structures has not been clearly investigated to ensure its structural application and safety. Flax FRP sheets usually contain fibers in two orthogonal directions, termed as warp and weft directions as shown in Fig. 1. It was found in this study that tensile strength, elastic modulus and fracturing strain are different in the different fiber direction. In the weft direction, their tensile strength and stiffness tend to be stronger than that in the warp direction. On the other hand, in the warp direction the fracturing strain is higher than that in the weft direction. This research aims for the first time to study shear strengthening of RC beams jacketed by flax FRP. In this study, tensile test of flax FRP coupons was conducted to investigate their mechanical properties. To examine the structural performance of RC beams jacketed by flax FRP, in total seven rectangular beam specimens were prepared including one control specimen without flax-FRP jacketing. Three specimens were jacketed in which the weft direction was set normal to the member axis, while the other three specimens had the warp direction set normal to the member axis. The number of flax sheet layers is one, two and three for each group of three specimens. All the six specimens with jacketing showed similar shear failure immediately after the tensile fracture of flax fiber sheet along a main shear crack. The enhancement of shear strength could be observed in all jacketed specimens. This fact proved that flax FRP can effectively increase shear strength. In addition, the experimental shear strength of RC beams was compared with that obtained from design equation of JSCE code in order to investigate its applicability.

2. TEST PROGRAMS

2.1 Material test

(1) FRP coupon

Tensile properties of flax fibers are imperative in order to consider them as reinforcement. To that purpose, coupon test of flax FRP was conducted considering fiber alignment in both warp and weft directions with nominal fiber mass of 128 and 120 g/m^2, respectively. The properties of the epoxy resin used in the test to uniformly gather the fibers are shown in Table 1. From the flax fiber sheet (see Fig. 1 (a)), three coupon specimens with warp and weft fiber directions were prepared based on JSCE standard [4],

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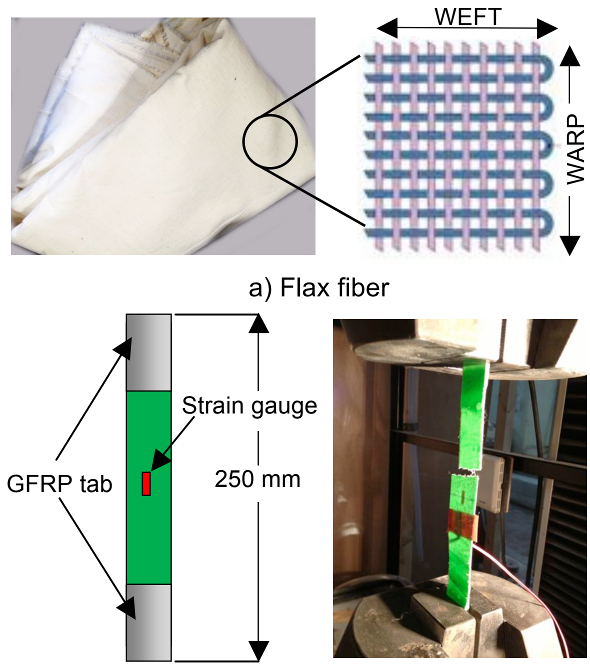
as shown in Fig. 1 (b). The geometry of specimens is shown in Table 2. All specimens were coated with epoxy resin, and cured for a week. GFRP tabs were attached at the both edges of specimens to prevent from slipping between specimen and the wedge grip of the tensile machine. Strain gauges were attached at the mid-height of each specimen. The test setup for a coupon test is shown in Fig. 1 (c).

Table 1 Properties of epoxy resin

Name	No.	Bending strength MPa	Tensile strength MPa	Elastic modulus MPa
Dine FF	D-90	≥40	≥30	2,350



a) Flax fiber

b) Coupon specimen c) Test setup

Fig. 1 Flax fiber, coupon test setup and specimen

From the coupon test, tensile strength, elastic modulus and rupture strain were obtained and the summary of results of tensile test for six coupon specimens are shown in Table 2. Coupon specimens for WARP and WEFT were denoted as WARP1 to WARP3 and WEFT1 to WEFT3, respectively.

Table 2 Summary of result of tensile test

Coupon	w_f mm	t_f mm	A_f mm^2	f_{fu} MPa	ε_u $\mu\varepsilon$	E_f MPa
WARP1	12.37	0.092	1.133	307.5	69,864	13,400
WARP2	12.32	0.092	1.128	270.0	62,610	15,300
WARP3	12.38	0.092	1.134	251.3	31,047	15,300
WEFT1	13.09	0.086	1.122	498.4	25,739	18,500
WEFT2	13.22	0.086	1.133	361.1	19,481	20,300
WEFT3	12.63	0.086	1.082	508.3	26,296	20,800

* w_f = width, t_f = nominal thickness, A_f = area, f_{fu} = tensile strength, ε_u = fracture strain, and E_f = elastic modulus of coupon specimens.

Stress-strain curve of the six coupon specimens is shown in Fig. 2. While WARP specimens showed higher fracture strain than WEFT specimens, the latter showed higher strength than the former. Therefore, the difference in fiber direction affects the load-carrying capacity and ductility of strengthening of RC members after strengthening by flax fiber jacketing.

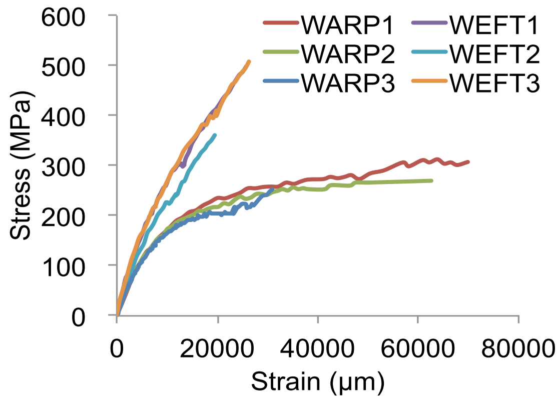


Fig. 2 Stress-strain curve of coupon specimens

(2) Concrete and steel reinforcement

The compressive strength was 33 MPa at 14 days using high early strength cement with coarse aggregate having maximum size of 20 mm. Slump value was set to be less than 150 mm. Casting of the beams was made with ready mixed concrete in stiff steel molds placed horizontally. Longitudinal reinforcement used in the beam test had diameter of 25 mm and yielding strength of 539 MPa, whereas stirrup used had diameter of 6 mm and yielding strength of 350 MPa. The properties of steel reinforcement are shown in Table 3.

Table 3 Properties of steel reinforcement

Type	Diameter mm	Area mm^2	f_y MPa	E_s MPa	ε_y $\mu\varepsilon$
Longitudinal	D25	507	539	188,000	2,100
Stirrup	D6	31.7	350	153,000	2,000

* E_s= elastic modulus, f_y = yielding strength and ε_y = yielding strain.

2.2 Beam test

After observing the tensile testing results of flax-FRP coupon specimens, loading test for beam specimens with and without FRP jacketing were conducted. All seven beam specimens were loaded statically to their ultimate state by a hydraulic jack. Each specimen had a cross section ($b \times h$) of 250 mm × 270 mm, whose corners were chamfered with a radius of 11 mm to prevent stress concentration in the flax sheet, and the shear span a was 600 mm, resulting in a shear-span to effective-depth ratio of 2.50. The spacing of stirrups was 150 mm in all specimens. The longitudinal reinforcement and stirrup ratios were 3.40% and 0.17%, respectively, in all seven specimens, whereas the volumetric ratio (i.e., calculated using the nominal thickness of the FRP sheets) of the wrapped flax-FRP composites varied from 0.07 % to 0.21%. Continuous flax-FRP sheets with the main fibers oriented in the transverse direction were fully wrapped around the RC beam. The main direction of flax FRP was in either WARP or WEFT directions while the number of flax-FRP layers was the experimental parameters. The details of seven beam specimens are shown in Table 4.

Table 4 Details of beam specimens

Specimen	Layer No.	ρ_f %	b mm	d mm	h mm	a mm
Control	-	0	250	240	270	600
WARP1	1	0.07	250	240	270	600
WARP2	2	0.15	250	240	270	600
WARP3	3	0.22	250	240	270	600
WEFT1	1	0.07	250	240	270	600
WEFT2	2	0.14	250	240	270	600
WEFT3	3	0.21	250	240	270	600

Strains of longitudinal reinforcement, stirrups and flax-FRP sheet were measured using strain gauges. The strain gauges were located in the region where shear cracks were expected to occur. Displacement at mid-span and supports were measured using Linear Variable Differential Transducers (LVDT). The characteristics of beam specimens, test setup, and location of strain gauges are shown in Fig. 3.

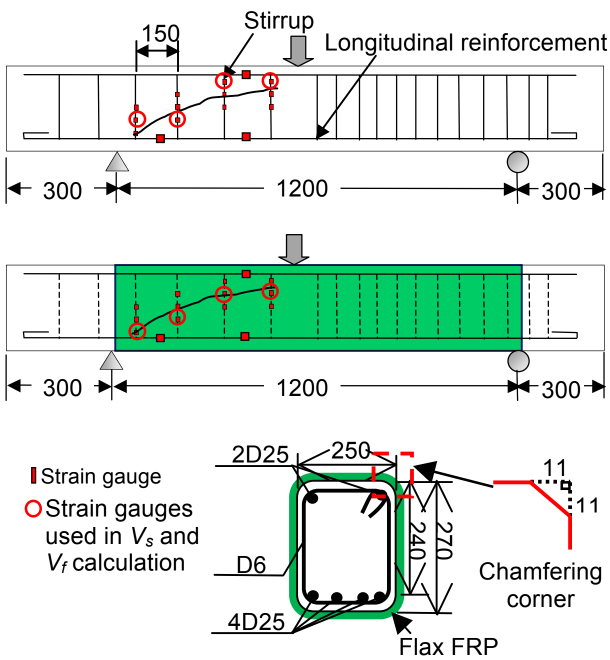


Fig. 3 Characteristics of beam specimens, test setup and location of strain gauges

3. EXPERIMENTAL RESULTS

3.1 Failure modes

Failure modes before and after removing flax-FRP sheets are shown in Figs. 4 and 5. Control specimen showed concrete crushing along main shear crack with loud noise of crack opening when the peak load was reached. In case of all six specimens with flax-FRP jacketing, they all failed in shear with FRP rupture along shear cracks. According to the test results, the longitudinal reinforcement in the control specimen yielded at the near support. It is evident that shear-crack opening significantly affects to the yielding of such longitudinal reinforcement. This phenomenon is commonly known as tension shift effect.

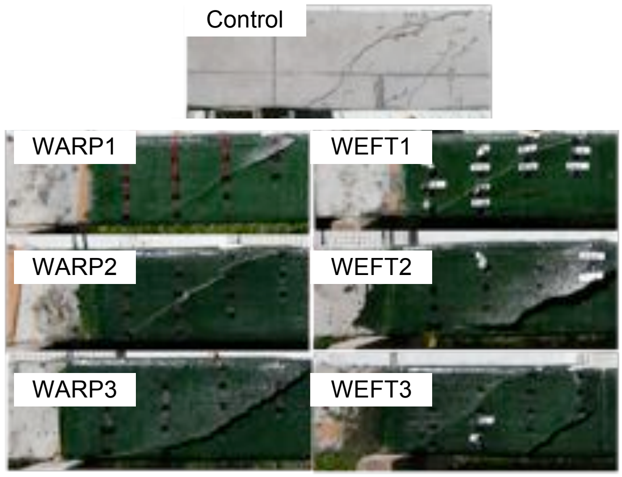


Fig. 4 Failure modes before removing fiber sheets

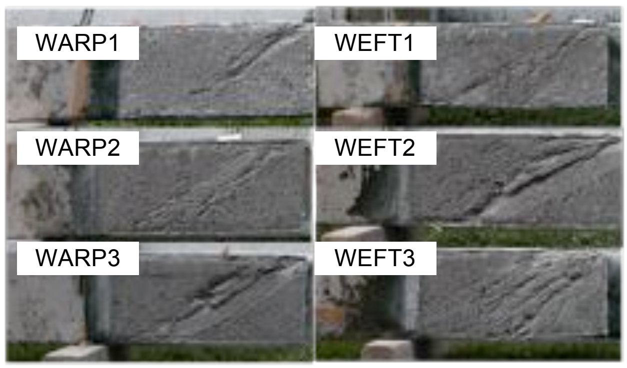


Fig. 5 Failure modes after removing fiber sheets

3.2 Shear-force and vertical-displacement relationships

Relationships between shear force and vertical displacement at mid-span are shown in Figs. 6, 7 and 8. Figs. 6 and 7 show such relationships of RC beams jacketed by WARP and WEFT FRP sheets, respectively. Fig. 8 shows the shear force-displacement relationships of all beam specimens. Shear strengths of both WARP and WEFT specimens are enhanced obviously when the number of layers of flax FRP applied increases. Displacements at the peak load also increase gradually when increasing the number of layers of flax FRP. Therefore, wrapping flax fiber sheets on RC beams has shear strengthening effect. Comparing WARP with WEFT specimens, maximum shear strength and corresponding displacement of WEFT specimens are higher than those of WARP specimens, as shown in Fig. 8. The enhanced shear strength increases with the amount of flax FRP. The enhancements of shear strength are from 45% to 72% for WEFT specimens and from 22% to 67% for WARP specimens. Despite the difference in the tensile strength and fracture strain, both WEFT and WARP specimens show similar efficiency in shear strengthening. Jacketing with flax-FRP sheet in WEFT direction would improve more shear strengthening effect for the RC beams than jacketing in WARP direction.

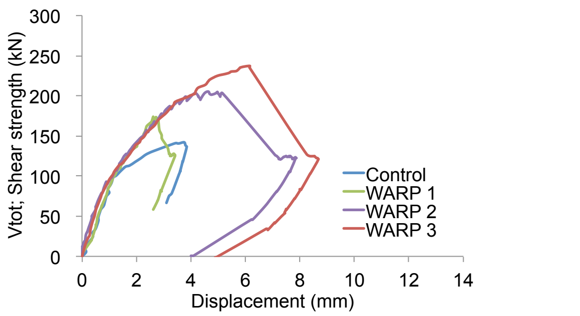


Fig. 6 Relation between shear force and vertical displacement of WARP specimens

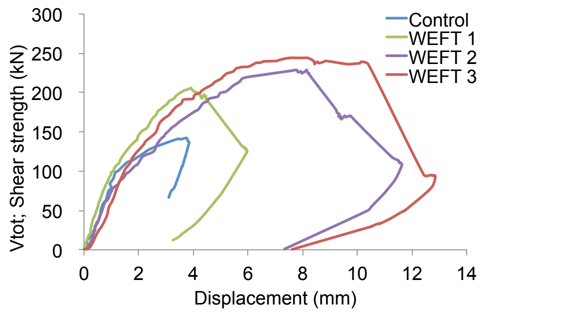


Fig. 7 Relation between shear force and vertical displacement of WEFT specimens

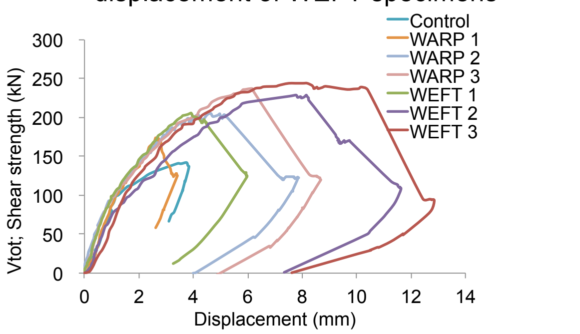


Fig. 8 Relation between shear force and vertical displacement of RC beams

3.3 Shear force components

Total shear force (V_{tot}) consists of shear forces carried by concrete (V_c), stirrup (V_s) and NFRP sheet (V_f), as shown in Eq. (1). Shear forces carried by stirrup and FRP sheet are calculated using strains of stirrup and FRP sheet measured along shear crack, as shown in Fig. 3 (see strain gauges in circles). Shear force carried by concrete (V_c) can be obtained by subtracting the total shear force with the shear force carried by stirrup and FRP (V_{tot}-V_s-V_f). The equation for the total shear force is show as below.

$$V_{total} = V_c + V_s + V_f \qquad (1)$$

Shear force carried by concrete, stirrup and flax-FRP sheets are shown in Fig. 9.

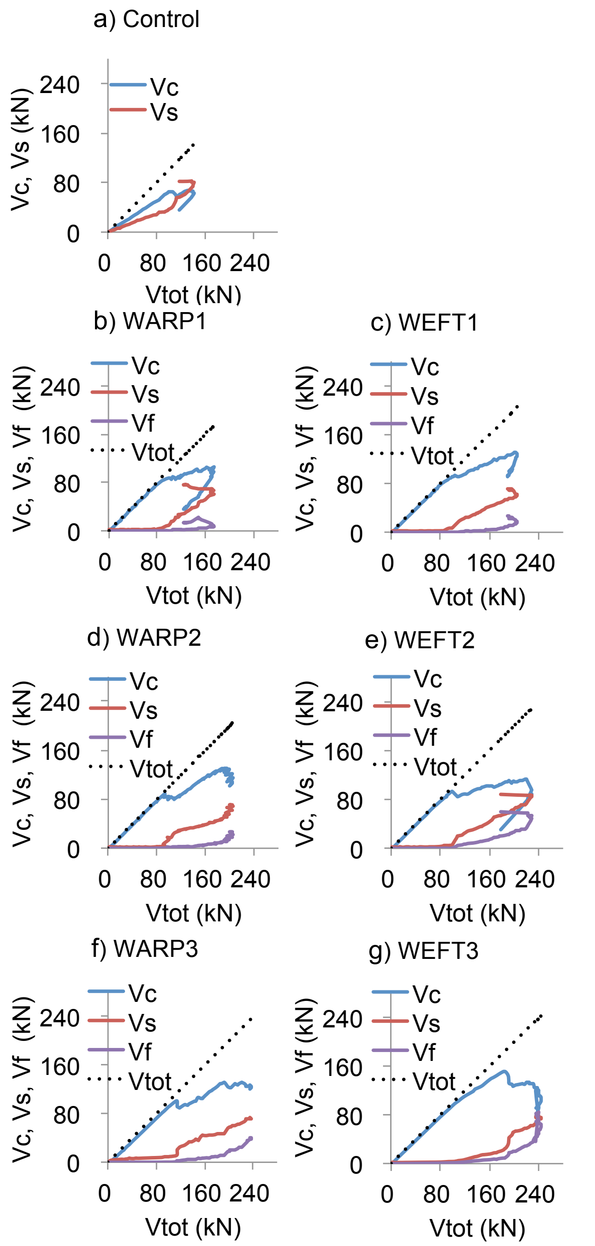


Fig. 9 Contributions of each shear force component to total shear force

In all beam specimens, stirrup and FRP sheet started carrying shear force when first shear crack exhibited with the load over 100 kN. When the number of layer of FRP sheets increases, shear force carried by FRP (V_f) increases in both of WARP and WEFT specimens. In WEFT specimens, V_f at the peak load contributes approximately twice as large as that in the WARP specimens. This is because the tensile strength of WEFT specimen is larger than WARP specimen.

3.4 Concrete shear force

As shown in Eq.(1), the concrete shear force can be calculated from the total member shear force once the shear contributions of stirrup and FRP sheets are known from the analyses on strain readings. The concrete shear force in RC members wrapped with flax-FRP sheets was found to have reached its peak value before the full development of the member shear strength, as shown in Fig. 10. Concrete shear force of beam specimens with flax-FRP jacketing increases comparing to that of control beam. It can be seen that concrete shear force increases when increasing the number of FRP layers. This indicates that flax-FRP confines and prevents the shear crack opening of concrete, leading to higher concrete contribution to shear resistance.

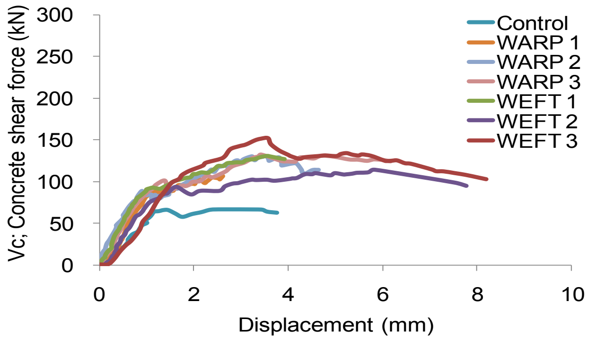


Fig. 10 Relationship between concrete shear force and vertical displacement

3.5 Strain development in stirrups and FRP sheets

Fig. 11 shows the development of the average strains in stirrups with the vertical displacement at mid-span until the peak load. The average strains of stirrups are the average values of all strain readings on each stirrup across the shear crack (see strain gauges with circles in Fig. 3). In the control specimen, increment of strain development in stirrups is higher than the other specimens jacketed by flax FRP. This might be because the shear crack propagation is faster in control specimen, leading to greater increase in strain. In all the strengthened beams, the stirrups have yielded before the peak load was reached. After yielding point, the increment of strain becomes faster until peak load has been reached.

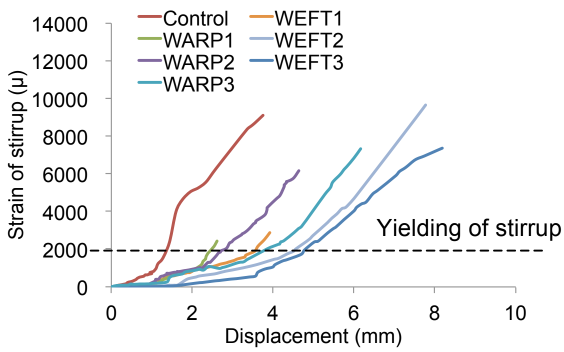


Fig. 11 Strain increments of stirrups

Fig. 12 shows the development of the average strains in flax-FRP sheet with the vertical displacement at mid-span until the peak load. An approximately linear increase of the average strains with the vertical displacement was seen before yielding of stirrups. After yielding, the strain increase in flax-FRP sheets behaved nonlinearly. Moreover, the rate of strain increase in flax-FRP sheets increased after yielding due to the stiffness degradation of the stirrups. In addition, the large strain values observed in flax-FRP sheets at the peak loads (i.e., 9,000–13,000 $\mu\varepsilon$ for WEFT specimens and 5,000–9,000 $\mu\varepsilon$ for WARP specimens) demonstrate the significance of using difference in fiber direction of flax-FRP sheets and the number of layer applied. The more layers of flax-FRP are applied, the higher strain development for maintaining the integrity and ductility of RC members can be observed.

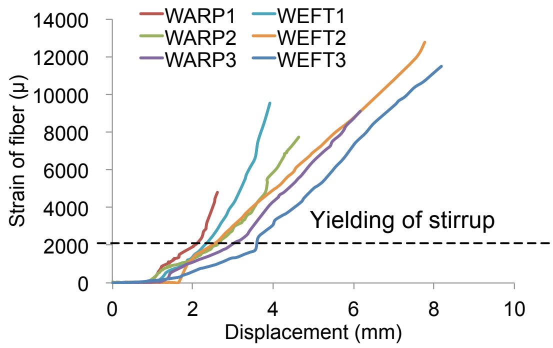


Fig. 12 Strain distributions of flax-FRP sheets

4. DISCUSSIONS

4.1 Comparison between flax FRP and PET FRP

Since the flax fiber sheet has a rather low elastic modulus, the result of RC beam with the same dimension ($b \times h$ = 250 mm × 270 mm), shear span (600 mm) and stirrup ratio (0.17%) as those flax FRP specimens, jacketed by PET sheet whose elastic modulus is also low [5], was compared with the beams with the flax FRP. The tension reinforcement ratio was slightly higher (4.22 % compared with 3.40 % of specimen with flax FRP). Fig. 13 presents a comparison of three RC beams jacketed by different types of FRP jackets, WARP, WEFT and PET FRP sheets, for the same amount of FRP ratio (i.e., ρ_f = 0.21-0.22%). It can be seen that with the same amount of FRP ratio, RC members jacketed by flax-FRP sheet show the similar shear strength enhancement, namely nonlinear increase until peak-load, although the sheet stiffness and tension reinforcement were less.

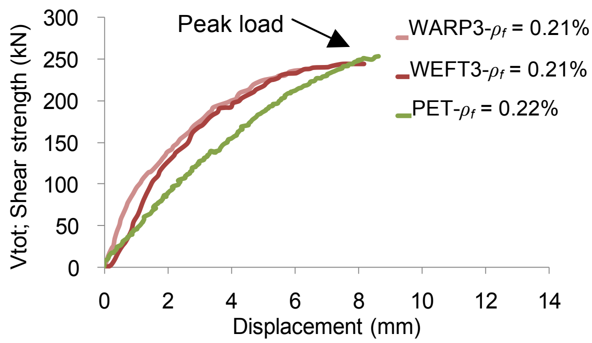


Fig. 13 Comparison between RC beams jacketed by flax FRP and PET FRP sheets

4.2 Applicability of existing design equation

To predict shear strength of beam strengthened by flax FRP, shear strength obtained from experiment and JSCE code [6] are compared. Total shear strength can be calculated from Eq. (1). The concrete and stirrup contributions to shear strength can be calculated as follows:

$$V_c = 0.2\sqrt[3]{f_c'}\sqrt[4]{1000/d}\sqrt[3]{100\rho_w}(bd) \qquad (2)$$

$$V_s = A_w f_{wy}(\sin\alpha_s + \cos\alpha_s)z/s \qquad (3)$$

where f'_c is the compressive strength of concrete; b is the width of member, d is the effective depth of member; ρ_w is the ratio of transverse steel reinforcement; A_w is the cross-sectional area of transverse steel reinforcement; f_{wy} is the yielding strength of transverse reinforcement; α_s is the angle of transverse steel reinforcement to the member's axis; and z is d/1.15; s is the spacing of shear reinforcement. The shear contribution provided by FRP sheet is its tensile capacity and is computed based on the shear reinforcing efficiency of the FRP sheet (K) as shown in Eq. (4).

$$V_f = KA_f f_{fu}(\sin\alpha_f + \cos\alpha_f)z/s_f \qquad (4)$$

where K=1.68-0.67R in which $0.4 \le K \le 0.8$ and $R = (\rho_f E_f)^{1/4}(f_{fu}/E_f)^{2/3}(1/f_c')^{1/3}$ in which $0.5 \le R \le 2.0$; A_f is the cross-sectional area of the FRP sheet; f_{fu} is the design tensile strength of the FRP sheet (N/mm^2); s_f is the spacing of the FRP sheet; E_f is the modulus of elasticity of the FRP sheet (kN/mm^2); ρ_f is the volumetric ratio of the FRP sheet; and α_f is the angle of the FRP sheet to the member axis. Comparison of shear strength between JSCE code and experiment is shown in Fig. 14. V_{tot} of JSCE code is quite conservative as shown in the figure. This is partly because the equation of JSCE does not consider the confinement effect by jacketing sheet [7].

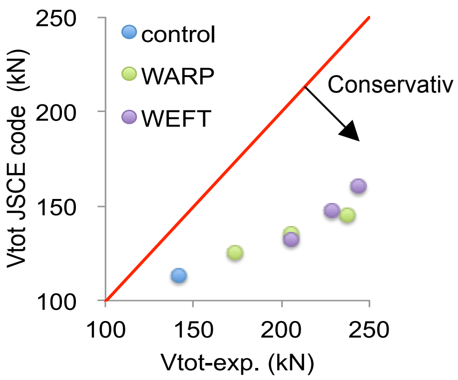


Fig. 14 Comparison between shear strength from experiment and JSCE code

5. CONCLUSIONS

(1) Flax fiber is an effective material for strengthening of RC beams. WEFT direction is the better way to wrap flax fiber on RC structures for shear strengthening.
(2) Increasing the number of flax-FRP sheet layer can increase the total shear strength and concrete shear strength. The enhancements of shear strength are from 45% to 72% for WEFT specimens and from 22% to 67% for WARP specimens.
(3) The design equation in JSCE code underestimates the shear strength of beams with flax-FRP sheet
(4) Comparing with RC members jacketed with PET-FRP sheets, flax-FRP sheets, whose stiffness is smaller, can enhance shear strength as much as PET-FRP sheet.

ACKNOWLEDGEMENT

The authors would like to acknowledge Professor XIAN Guijun at Harbin Institute of Technology, for providing invaluable advice and the flax fiber sheet. The authors are also grateful to the Maeda Kosen Co. Ltd., Japan for providing for providing epoxy resins for this study.

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