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SHEAR UPGRADING OF REINFORCED CONCRETE BEAMS WITH EXTERNALLY BONDED COMPOSITE SHEETS

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ABSTRACT: Experiments were conducted to investigate the shear behavior of RC beams strengthened with externally bonded FRP sheets. Nine RC beams strengthened using CFRP and AFRP sheets were tested. Study was focused on effective utilization of FRP sheets to prevent debonding of sheet. It was found that both CFRP and AFRP sheets possess excellent capability to enhance shear capacity of RC beams and sheet debonding can be prevented by providing anchorage of additional length of sheet at the top surface of the beam. Design methodologies proposed by different researchers to calculate the FRP contribution to shear capacity is also discussed and compared with the experimental results.

KEYWORDS: bond strength, epoxy resin, FRP sheet, RC beams, shear strengthening

1. INTRODUCTION

Strengthening and repairing deteriorating reinforced concrete (RC) structures has now become a major challenge to construction industry all over the world. RC structures deteriorate due to many reasons such as corrosion of internal reinforcement, chloride attack, carbonation, freeze-thaw action, etc. Furthermore, poor initial design and construction faults also render existing RC structure deficient. However, the most important reason for strengthening RC structures is due to upgrading of design codes and increased vehicle loads. In Japan, the design vehicle load for highway bridges has recently been increased from 196 kN to 245 kN, which has created the safety and reliability problem for several existing bridge structures. In particular, the shear requirement in this situation has become more stringent for highway bridge structures. Such deficient structures have to be either replaced or upgraded in order to maintain efficient transportation network. Over the years, innovative techniques for upgrading of RC structures have been invented such as external prestressing and external bonding of steel plates or fiber reinforced plastics (FRPs). Through intensive research and development, flexible FRP sheets have brought new and innovative solutions for strengthening of existing RC structures. The advantages offered by FRPs are high mechanical properties, lightweight, corrosion resistance, non-magnetic, low scaffolding and labor cost and less interruption during application.

Bond of FRP sheet to concrete is of critical importance for effectiveness of strengthening technique using externally bonded FRP sheets. Because of low bond strength, failure occurs due to debonding of FRP prior to achieving full tensile strength of FRP sheet. Such a mode of failure diminishes the strengthening potential of externally bonded sheets. This paper presents the shear behavior of RC beams strengthened with FRP sheets and influence of anchorage of sheets on the top surface of the beam on sheet debonding. The provision of anchorage by sheet itself is found to be very effective, practical, and easy technique to avoid debonding between the sheet and concrete.

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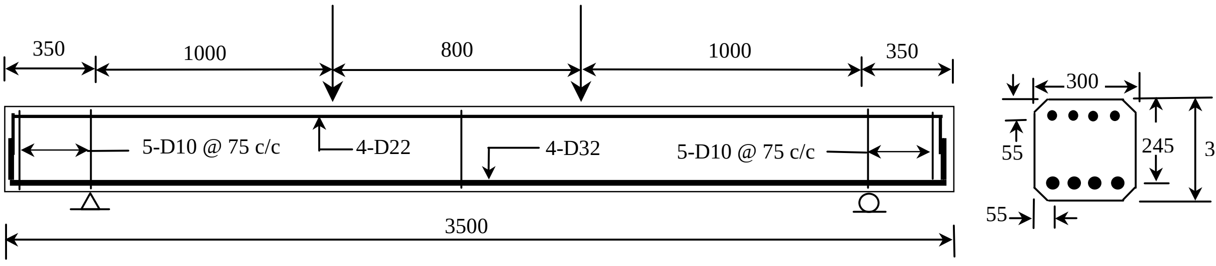
2. EXPERIMENTS

Fig. 1 shows the dimensions of RC beams used in the test. All beams had the same cross section, flexural reinforcements, and a clear span of 2800 mm. Since all beams were designed to fail in shear before the yielding of longitudinal reinforcement, stirrups were not provided. Mechanical properties of the FRP sheets and the reinforcing bars are shown in **Table 1** and **Table 2** respectively.

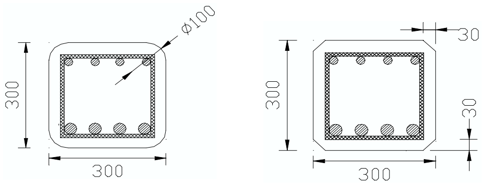


(Dimensions in mm)

Fig. 1 Beam details

Beam B-1 was the control beam without strengthening. Four beams were strengthened using CFRP sheets, while the other four were strengthened using AFRP sheets. FRP sheets used were unidirectional, where principal fibers were kept perpendicular to the longitudinal axis of the beams. To reduce the stress concentration in the sheet at sharp corners, the cross section of the beams were chamfered at 30 mm in AFRP sheet bonded beams. On the other hand, the chamfered edges were further smoothened in a round shape at 100 mm diameter in CFRP sheet bonded beams due to relatively stiffer nature of CFRP sheets compared to AFRP sheets [**Fig. 2**].

Fig. 3 shows the typical bonding pattern of the sheets and **Fig. 4** shows the wrapping layouts of FRP sheets and bonded anchorage on the top surface of the beams.



CFRP Series **AFRP Series**

Fig. 2 Details at section edge

(Dimensions in mm)

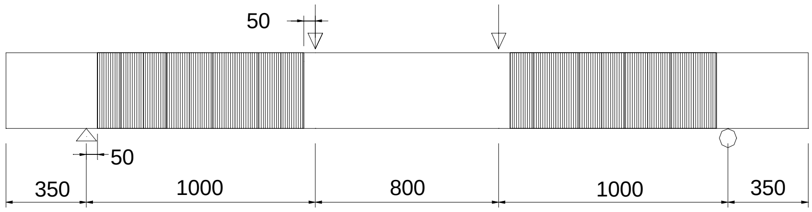


Fig. 3 Typical sheet bonding layout

(Dimensions in mm)

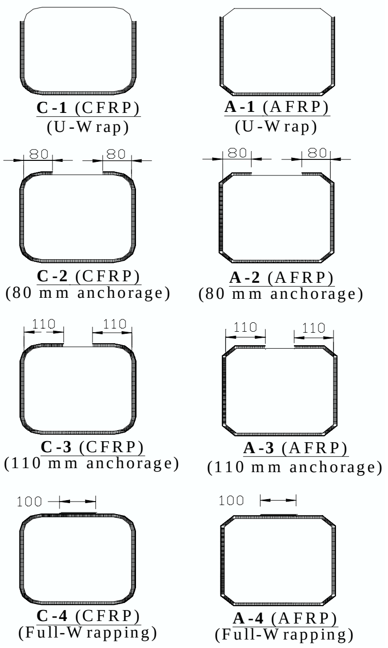


Fig. 4 Sheet wrapping scheme

Table 1 Properties of FRP sheets

	Design thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Ultimate elongation (%)
CFRP	0.167	3400	230	1.5
AFRP	0.286	2000	120	1.8

Table 2 Properties of reinforcement

	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (GPa)
D-32	398	574	206
D-22	391	570	186

3. EXPERIMENTAL RESULTS AND DISCUSSION

The ultimate failure loads, shear contributed by FRP sheet (V_f), and increase in shear capacity over the control beam for all beams are shown in **Table 3**. The V_f values are as obtained by subtracting the shear strength of control beam from the shear strength of respective strengthened beams, i.e., a constant V_c is assumed, which is an acceptable procedure for simplicity of calculation.

Table 3 Test results

Beam series		*Failure load (kN)	V_f (kN)	Increase (%)	Failure mode
Control	B-1	224.0	-	-	Diagonal shear
CFRP	C-1	330.0	53.0	47.3	Diagonal shear + debonding
	C-2	457.0	116.5	104.0	Diagonal shear + splitting
	C-3	475.0	125.5	112.0	Diagonal shear + splitting
	C-4	500.0	138.0	123.2	Flexure + concrete crushing
AFRP	A-1	310.0	43.0	38.4	Diagonal shear + debonding
	A-2	400.0	88.0	78.6	Diagonal shear + splitting
	A-3	490.0	133.0	118.8	Diagonal shear + splitting
	A-4	488.0	132.0	117.9	Flexure + concrete crushing

*Shear strength of beam is half of failure load; +average load for flexural failure for all beams is 506 kN.

3.1 FAILURE LOADS AND FAILURE MODES

The final failures of beams C-1 and C-2 are shown in **Fig. 5**. Beams C-1 and A-1, which were strengthened by U-wrap of CFRP, and AFRP respectively, failed in diagonal shear followed by the debonding of sheet. Beams C-2 and A-2 strengthened with anchorage of sheet at the top surface of beams showed higher load carrying capacity and did not show sheet debonding. The ultimate failure mode for both the beams was concrete splitting, which occurred on a vertical plane along the compression reinforcement. Beams C-2 and A-2 showed an increase of 120.0 % and 104.7 % in shear capacity compared to beams C-1 and A-1 respectively. Longer bonded anchorage of 110 mm was provided in beams C-3 and A-3, which failed in the same manner as beams C-2 and A-2. Beams C-4 and A-4 strengthened with full wrapping of CFRP and AFRP sheets failed in flexure. **Fig. 6** shows the load displacement relationships for CFRP and AFRP series beams. As seen from this figure that though the beam A-3 and A-4 failed at almost same load level, the final failure in A-3 was due to shear and splitting after the yielding of reinforcement, whereas in beam A-4, failure was due to yielding and crushing of concrete. Because of full–wrapping of beam A-4, splitting failure was avoided, while beam A-3, though reached to yielding failed in splitting mode.

(a) Debonding of sheet in beam C-1

(b) Concrete splitting in beam C-2

Fig. 5 Observed failure modes

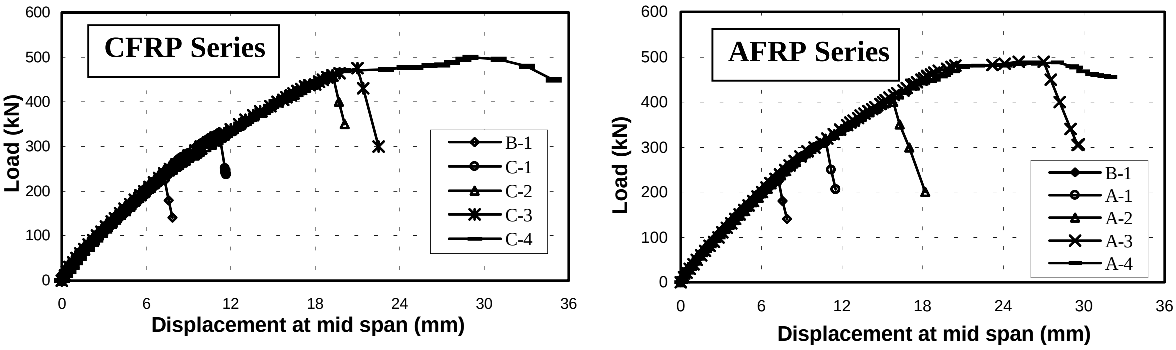


Fig. 6 Load vs. mid-span displacement relationship

3.2 STRAIN IN FRP SHEET

Fig. 7 shows the strains in the sheet in principal fiber direction for all strengthened beams. It is seen that in pre-diagonal cracking stage, strains are almost negligible. When the diagonal crack occurs, the strain in sheet increases rapidly contributing to the shear resistance of the beam. The increase continues until the failure of the beam occurs due to debonding, concrete splitting or flexure.

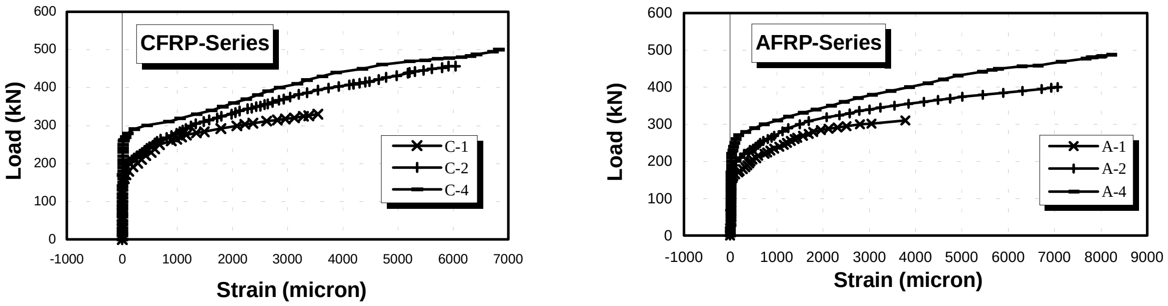
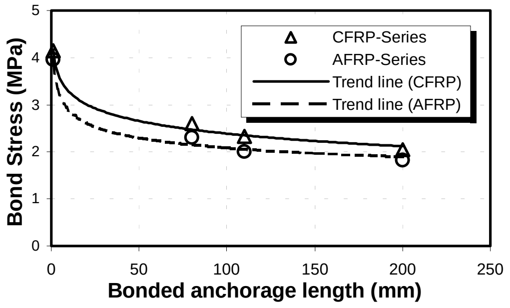


Fig. 7 Load vs. FRP vertical strain relationship

3.3 BOND STRESS AT THE INTERFACE

The average bond stresses at the concrete-epoxy-FRP interface at ultimate load were calculated from the strain gradient in the sheet at the location of shear crack. For sheet debonding in beams C-1 and A-1, average bond stress was found to be 4.05 MPa. **Fig. 8** shows the bond stress versus bonded anchorage length relationship. It is seen that the provision of bonded anchorage resulted in significant reduction in bond stress at the interface. **Fig. 9** shows that the effective strain in FRP sheet has significantly increased with the bonded anchorage length. More than 100 % increase in effective strain was achieved as a result of bonded anchorage thus resulting in an effective utilization of FRP sheet.



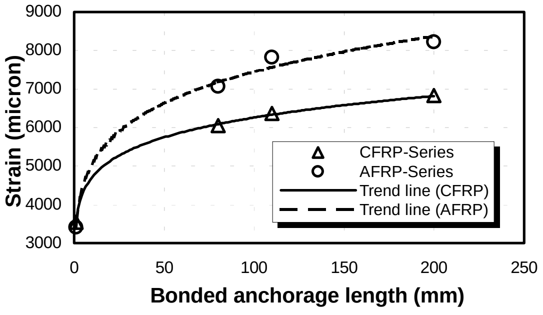


Fig. 8 Bond stress vs. bonded anchorage length **Fig. 9 Sheet strain vs. bonded anchorage length**

4. FRP SHEET CONTRIBUTION TO SHEAR CAPACITY

For RC beams with externally bonded FRP sheets, the shear strength may be computed by **Eq. 1**.

$$V_n = V_c + V_s + V_f \qquad (1)$$

where, V_c and V_s are the shear forces carried by concrete and web reinforcement and V_f is the contribution of externally bonded FRP. The external FRP reinforcement may be treated in analogy to the internal steel if it is accepted that FRP carries only the normal stresses in principal FRP material direction and at the ultimate state in shear FRP develops an effective strain ε_{fe} in the principal material direction that is less than the tensile failure strain ε_{fu}. Then, V_f for FRP sheets or strips can be calculated by **Eq. 2**.

$$V_f = \rho_f E_f \varepsilon_{fe} d_f b_w (\sin\beta + \cos\beta) \qquad (2)$$

where, ρ_f = FRP shear reinforcement ratio = $(2t_f/b_w)(w_f/s_f)$; t_f = thickness of FRP; w_f = width of FRP strip; s_f = spacing of FRP strips; E_f = elastic modulus of FRP; d_f = depth of the FRP sheet usually equal to effective depth of cross section; b_w = width of cross section and β = angle between the principal fiber and the longitudinal axis of the beam. Many researchers have proposed empirical equations to estimate the effective strain (ε_{fe}) in the sheet at failure; some of them are presented below and compared with the experimental values of V_f.

JSCE Code [1] $$V_f = K\left(A_f f_{fud}(\sin\beta + \cos\beta)/s_f\right)z/\gamma_b \qquad (3)$$

where, $A_f = 2\, t_f\, w_f$; K = shear reinforcing efficiency of FRP sheets = $1.68 - 0.67R$ but $0.4 \le K \le 0.8$; $R = (\rho_f E_f)^{1/4}[f_{fud}/E_f]^{2/3}(1/f'_{cd})^{1/3}$ and $(0.5 \le R \le 2.0)$; f_{fud}= design tensile strength of FRP sheet; z = lever arm length generally d / 1.15; γ_b = member factor generally 1.25 and f'_{cd} = tensile strength of concrete.

fib Code [2] $$V_f = 0.9\varepsilon_{fk,e}\, \rho_f E_f d_f b_w (\sin\beta + \cos\beta) \qquad (4)$$

For U-wrap FRP $$\varepsilon_{fe} = \min\left[0.65(f'^{2/3}_c/\rho_f E_f)^{0.56} \times 10^{-3},\ 0.17(f'^{2/3}_c/\rho_f E_f)^{0.3}\varepsilon_{fu}\right] \qquad (5)$$

(sheet debonding) (FRP rupture)

For full wrap CFRP $$\varepsilon_{fe} = 0.17\,(f'^{2/3}_c/\rho_f E_f)^{0.3}\varepsilon_{fu} \qquad (6)$$

For full wrap AFRP $$\varepsilon_{fe} = 0.048\,(f'^{2/3}_c/\rho_f E_f)^{0.47}\varepsilon_{fu} \qquad (7)$$

and $\varepsilon_{fk,e} = \alpha\varepsilon_{fe} \le \varepsilon_{max}$ where, $\alpha = 0.8$ and $\varepsilon_{max} = 0.005$

Triantafillou and Antonopoulos [3] $$V_f = \varepsilon_{feA}\rho_f E_f b_w d\,(\sin\beta + \cos\beta) \qquad (8)$$

where, $\varepsilon_{feA} = 0.9\,\varepsilon_{fe} \le \varepsilon_{max,A}$ and $\varepsilon_{max,A} = 0.006$

Khalifa et al. [4] Authors proposed two design approaches and suggested taking the minimum as design value of V_f. First one is based on an effective strain in FRP sheet, for which **Eq. 2** is used, where $\varepsilon_{fe} = R\,\varepsilon_{fu}$ and ε_{fu} is the ultimate strain of FRP sheet, while R is given by **Eq. 9**.

$$R = 0.5622\,(\rho_f E_f)^2 - 1.2188\,(\rho_f E_f) + 0.788 \le 0.50 \qquad (9)$$

Second approach is based on the bond mechanism and V_f is given by **Eq. 10**.

$$V_f = 2\ L_e\ w_{fe}\ \tau_{bu} \qquad (10)$$

where, L_e = effective bond length = $e^{6.134 - 0.58ln(tfEf)}$; w_{fe} = effective width of FRP sheet = $d_f - L_e$; τ_{bu} = average bond stress = $k\ (f'_c / 42)^{2/3}\ E_f t_f$ and k = average strain gradient = 110.2x10^{-6} 1/mm.

Table 4 shows the comparison between the empirical and experimental values of V_f. None of the equations except the proposed by JSCE is able to predict V_f correctly as observed in the experiments. The reason is that the detailed investigation on shear strengthening of RC members using externally bonded FRP sheets have been relatively limited and to certain degree controversial. Due to the lack of adequate laboratory data, it is difficult to standardization a design equation taking into account of all factors affecting the FRP sheets contribution to the shear capacity of beams (V_f).

Table 4 Contribution of FRP sheet (V_f) in kN

Reference research	U-wrap		Full-wrap	
	CFRP	AFRP	CFRP	AFRP
JSCE [1]	-	-	135.8	133.4
Fib [2]	63.9	62.3	74.1	66.4
Triantafillou and Antonopoulos [3]	80.0	77.8	99.1	88.6
Khalifa et al. [4]	69.2	67.0	101.0	98.3
Present expriment	53.0	43.0	138.0	132.0

5. CONCLUSIONS

1. Effectiveness of externally bonded CFRP and AFRP sheets for shear strengthening of RC beams was confirmed. A maximum of 123% increase for CFRP and 118 % increase for AFRP in shear capacity of beams were observed as compared to that of control beam.
2. It is confirmed that the FRP sheet with bonded anchorage is much more effective than U-wrap scheme and that the provision of bonded anchorage is an effective way to inhibit sheet debonding.
3. Bonded anchorage of sheet at the top surface of beam resulted in a decrease of interface bond stress.
4. Provision of bonded anchorage showed an increase of more than 100 % in effective strain of FRP sheet at failure as compared to the U-wrapped beams.

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