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SHEAR STRENGTHENING OF R/C BEAMS USING AFRP STIRRUPS WITH ANCHORED ENDS

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Abstract: Many studies have been conducted on the behaviour of reinforced concrete (R/C) beams shear-strengthened with fiber reinforced polymer (FRP) sheets. The studies show that FRP materials can produce good performance when used to carry some portions of shear force in the shear-strengthened beam. However, the performance of the FRP sheets used for shear strengthening is found limited by bond capacity between the FRP sheets and concrete surface. To improve the bond performance, an anchorage system can be introduced to the FRP strengthening scheme. This paper presents experimental and analytical studies conducted to evaluate the contribution and behaviour of aramid fiber reinforced polymer (AFRP) sheets with anchored ends in carrying the shear force in reinforced concrete beams. In the study, nine reinforced concrete beam specimens were fabricated and tested. Test parameters of the study include thickness of AFRP sheet used, type of wraps applied, type of anchors and diameter of anchor head used. Two types of anchorage system were proposed in the study, i.e. insert anchor system and **C**-embedded anchor system. The results from this study showed that the proposed anchorage system can improve the contribution of the FRP sheets in carrying the shear force in beams. In addition, the **C**-embedded anchor system exhibits better performance than the insert anchor system. Lastly, the behaviour of beams strengthened using FRP stirrups with anchored ends can be closely predicted by the ACI 440 design equations applicable for full-wrap scheme.

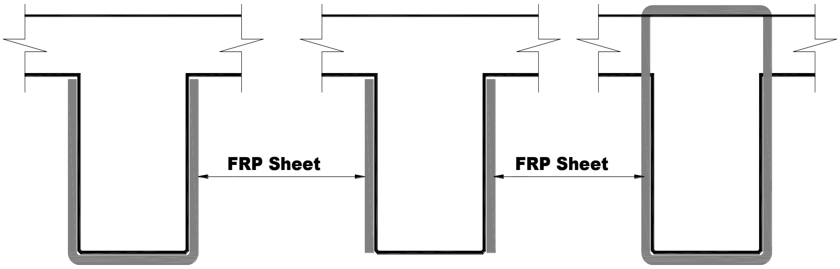
Keywords: *Fiber Reinforced Polymer (FRP) sheets*; *Shear strengthening*; *Bond capacity*; ***C**-embedded anchor*; *Insert anchor.*

1.0 Introduction

The changes in building functions, the revisions of the existing building codes or the increase in safety requirements are amongst the factors that may cause the need for structural strengthening in buildings. Types of strengthening methods that are commonly applied to reinforced concrete structures are concrete-jacketing, steel-jacketing, and external post-tensioning. Since the last decade, there is another type of concrete strengthening method that starts gaining popularity in the construction industry, i.e. FRP sheet-jacketing. This type of strengthening method uses FRP (*Fiber Reinforced Polymer*) sheets, made of glass (G), carbon (C) or aramid (A) fibers. The fibers in the FRP sheets have high tensile strength and therefore, they can be used to replace steel reinforcement in reinforced concrete members.

The resistance of structural elements that can be improved with the use of FRP sheets includes shear, flexural, torsion and axial resistance (ACI 440 2002). The strengthening method with the FRP sheet-jacketing is basically done by wrapping or attaching the FRP sheets on concrete surface using epoxy-based glue. Shear strengthening of concrete beams can be done through wrapping the FRP sheets around the beam sections, with the shape resembling stirrup reinforcement (ACI 440 2002). Type of wrapping schemes applied can be in the form of 2-sided wrap (S), 3-sided U-wrap (U) or full wrap (W) (Fig. 1). Wrapping schemes in the form of 2-sided wrap and U-wrap are mostly applied to reinforced concrete beams that are made integral with concrete slabs (T-beams). Full wrap (W) scheme can only be applied to a beam, where access to all four sides of the beam is available. Failure mechanisms of shear strengthening using FRP stirrups, especially those related to 2-sided wrap and U-wrap schemes, are usually in the form of debonding at the ends of FRP sheets (Imran et al. 2003, Chajes et al. 1995, Khalifa et al. 1998, and Adhikary et al. 2004). The performance of the FRP sheets in those types of strengthening schemes is not too effective. This is indicated by the low range of strain recorded on the FRP sheets at failure, which is only a fraction of the ultimate tensile strain (ε_{fu}) of the FRP sheets. Chajes et al. (1995) reported that the limiting strain of carbon FRP obtained from their experimental work is only about 0.5 %, i.e. around 30% of ε_{fu}. Based on the results of their tests, Imran et al. (2003) proposed the limiting strain value of 34 % of ε_{fu} (i.e. 0.6%) for Aramid fiber (AFRP) used with full wrap schemes. With other wrapping schemes, the effective strain of the FRP sheets at failure is much lower than those limits (Chajes et al. 1995, Imran et al. 2003 and ACI 440 2002).

The debonding type of failure in FRP shear-strengthened concrete beams with 2-sided wrap and U-wrap schemes can be minimized by introducing an anchorage system at the ends of FRP stirrups. By doing so, the effectiveness of the FRP sheets in carrying the shear force can be increased. Bousselham and Chaallal (2004) introduced FRP sheets with bonded anchorage for shear strengthening of R/C beams using U-wrap scheme. The bonded anchorage in their study is defined as the additional length of sheet extended to the top face of beams. From this study they found that specimens with bonded anchorage show 100% increase in FRP effective strain at failure. However, this bonded anchorage is applicable only to beams with a free top face, and not applicable to beams with monolithic slabs or T-beams. So, this type of strengthening scheme can not be applied to most beams in R/C buildings.



a) U-wrap (U) b) 2-Sided wrap (S) c) Full wrap (W)

Figure 1: Wrapping schemes for shear strengthening

Researches carried out to study the performance of shear strengthened R/C beams using FRP stirrups with other types of anchorage systems are still limited. A design guideline for this kind of shear strengthening is also not available at present. This paper presents the development of anchorage systems used to increase the effectiveness of FRP stirrups with U-wrap or 2-sided wrap schemes in carrying shear force in R/C beams. Two types of anchorage systems are proposed in the study, i.e. insert anchor system and **C-**embedded anchor system. An experimental study has been carried out by the authors to evaluate the effectiveness of the shear strengthened R/C beams using FRP stirrups with this kind of anchorage systems.

2.0 Experimental Program

2.1 Test Parameters and Details of Beam Specimens

Type of FRP sheets used in this study is AFRP (*Aramid Fiber Reinforced Polymer*), which is the product of PT. Fosroc Indonesia, with the brand name of Renderoc FR10. The epoxy resin used to glue the FRP sheets on concrete surfaces was Nitobond EP10. The characteristics of Renderoc FR10 and Nitobond EP10 can be seen in Table 1.

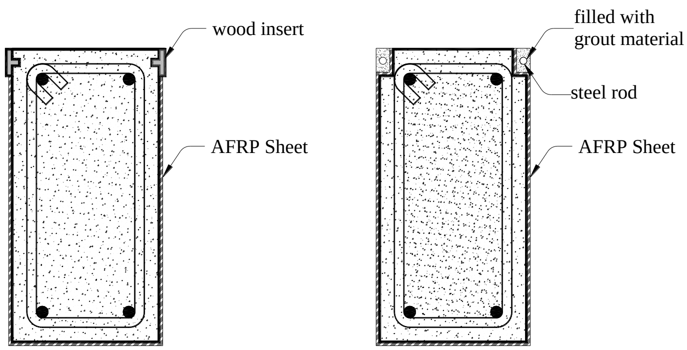
Table 1. Material characteristics of AFRP and epoxy resin

	AFRP AK 40	AFRP AK 60	Epoxy Resin
Thickness, mm	0.193	0.286	-
Adhesion Strength, MPa	-	-	8.5
Compr. Strength, MPa	-	-	80
Tensile Strength, MPa	2100	2100	15
Mod. of Elasticity, MPa	120000	120000	16000
Maximum Strain, %	1.8	1.8	-

In this study, 9 (nine) beam specimens, consisting of 1 (one) control beam and 8 (eight) test beams, with different test parameters, were fabricated and tested. Test parameters varied include:

a. Thickness of FRP sheets: AK-40 (0.193 mm) or AK-60 (0.286 mm)
b. Type of wrapping schemes: 2-sided wrap (S) or U-wrap (U)
c. Type of anchors: Insert or **C**-embedded
d. Diameter of anchor head for the insert anchors: 30 mm or 40 mm
e. Use of stirrups in shear span area: with or without stirrups

Of those test beams, 4 (four) test beams were shear strengthened using FRP sheets AK-40 with wrapping scheme of 2-sided (S) and 4(four) test beams were shear strengthened using FRP sheets AK-60 with wrapping scheme of U-wrap (U). Dimension of FRP sheets applied were the same for all test beams, i.e. the width (w_f) of 40 mm and center to center space (s_f) of 80 mm. The number of plies applied in the shear-strengthened beams was only one ply.



a) Insert anchor b) **C**-Embedded anchor

Figure 2: Anchorage systems developed in the study

Types of anchorage systems developed in this study can be seen in Fig. 2. Insert anchors were made of local wood species, i.e. "Kamper Medan" that has a good strength and durability. The anchors had the shaft diameter of 18 mm, length of 25 mm and head diameter of 30 or 40 mm. The anchors were inserted into pre-bored holes, in the test beams, that were pre-filled with epoxy resin before inserting the anchors.

The C-embedded anchors were made by precutting the corners of the beam cross-section, and then embedding the L-shaped ends of FRP sheets, followed by patching the precut corners with grout material. A small rod bar was used to hold the ends of the FRP sheets on their place before the precut corners were patched. Dimension of the precut corner applied in C-embedded anchor was 20x20x40 mm. The material used for grouting was the same as that used for gluing the FRP sheets to the concrete, i.e. epoxy resin.

Table 2: Variation of test parameters

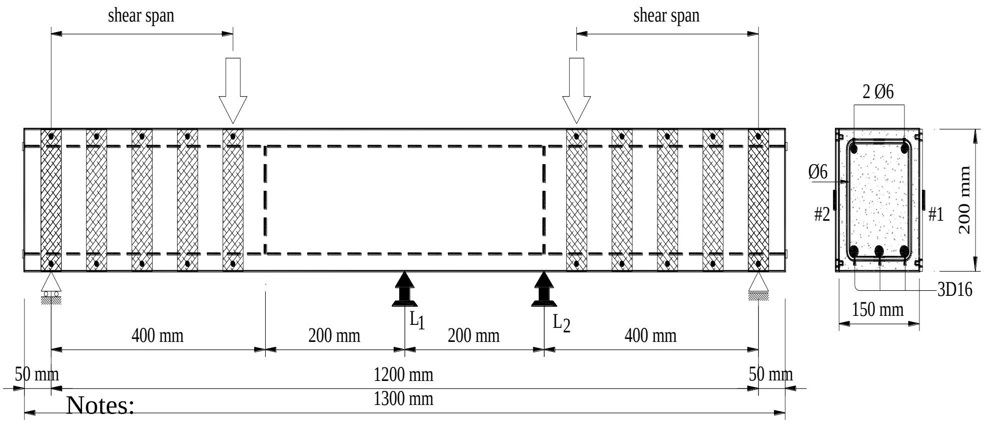
No	Sample Code	Wrapping Scheme	Width (w_f) mm	Space (s_f) mm	Anchor Types	*a/d*	ρ_{fe}
1	BK	-	-	-	-	1.83	-
2	S40-TA	S	40	80	TA	1.83	0.00128
3	U60-TA	U	40	80	TA	1.83	0.00191
4	S40-AC	S	40	80	AC	1.83	0.00128
5	U60-AC	U	40	80	AC	1.83	0.00191
6	S40-D30	S	40	80	D30	1.83	0.00128
7	U60-D40	U	40	80	D40	1.83	0.00191
8	S40-D30S	S	40	80	D30	1.94	0.00128
9	U60-D40S	U	40	80	D40	1.94	0.00191

Note:
BK = Control Beams ρ_{fe} = $(2.t_f.w_f)/(b_w.s_f)$
a/d = Shear span to depth ratio t_f = Thickness of FRP sheet
s_f = Center to center space between FRP sheets

Table 2 shows test parameters varied in this study. The sample code of the test specimens, consecutively from the left character, defines wrapping scheme applied, i.e. 2-sided (S) or U-wrap (U), and then followed by thickness of sheets used, i.e. 40 for AK-40 or 60 for AK-60. The next characters show type of anchors used, i.e. TA (no anchors), AC (C-embedded anchor), or D30 or D40 (insert anchor with head diameter of 30 mm or 40 mm). The last character, if exist, i.e. a letter S, shows the test beams with additional stirrup reinforcement along shear span area.

Geometry of the test beams was selected based on the available capacity of testing equipment and the desired mode of failure. Testing equipment used was a Universal Testing Machine with a capacity of 150 ton and the desired mode of failure in the test beams was shear failure. Based on these, the dimension of the beam cross-section was set to be 150x200 mm, with the length of beams of 1300 mm. To induce shear failure in the test beams, the shear capacity of the beams was made smaller than its corresponding flexural capacity. Figure 3 shows typical reinforcement and strengthening details of the test beams, along with the instrumentation used. Test beams S40–D30S and U60– D40S were reinforced with additional steel stirrups of ∅4.5-80 mm along the shear span area and additional longitudinal bottom reinforcement of 2D13. Other test beams did not have steel stirrups in the shear span area. Design of the test beams was carried out with referring to Indonesian Concrete Code (BSN, 2003).

During the casting of each test beam, two control cylindrical specimens of 150 by 300 mm size were made. Curing of the test specimens was carried out by covering the test beams and the control cylinders with wet burlaps. Before FRP sheets were glued, the concrete surface in the test beams was grinded to get smooth and level surface, and then cleaned from dirt, oil, and other harmful contaminants. Epoxy resin was then applied uniformly on the concrete surface before the FRP sheets were attached. After the FRP sheets were glued on to the concrete surface, the epoxy resin was again applied on the surface of FRP sheets to impregnate the fibers.



Notes:
#1 and #2 = strain gauges on FRP sheets
L_1 and L_2 = Displacement Transduces

Figure 3: Typical details of test specimens

2.2 Test Procedures

All beam specimens were tested as a simply supported member with third-point loading as shown in Fig. 4. Test specimens were tested under static monotonic loading using "Dartec Universal Testing Machine" with the maximum capacity of 150 ton at Structural Mechanics Laboratory of Institut Teknologi Bandung. The span of the test beams was 1200 mm, with the load applied at shear span *a* (Table 2). The tests were carried out when the concrete was 125 and 160 day old.

3.0 Results And Evaluation

3.1 Wood Material Tests

Wood material for insert anchor system should be strong, durable and locally available. Local wood species, i.e. "Kamper Medan", is known to satisfy those requirements. Because of that, "Kamper Medan" was used in this study. It had shear strength normal to wood fibers of 59 MPa and water content of 14 %. With this strength, the minimum shaft diameter of the anchor should be 18 mm so that the anchor material would not induce the failure of the shear-strengthening systems.

3.2 Steel Tensile Tests and Concrete Compression Tests

Tensile tests of reinforcing bars showed that the yield strength of steel reinforcement of diameter 4.5, 6, 13, and 16 mm were consecutively 295, 312, 515 and 560 MPa, and the tensile strength were consecutively 400, 415, 680 and 715 MPa.

The average compressive strength of the control cylindrical specimens were 36,84 MPa. The control cylinders were tested at the same time as the beams tests, i.e., when the concrete was 125 and 160 day old.

3.3 Shear Capacity of Test Beams

The load-deflection relationship of the test beams is shown in Fig. 5. The summary of the increase in shear capacity of the strengthened beams can be seen in Table 3. The table shows that the increase in shear capacity of test beams U60-TA and U60-D40 with respect to the shear capacity of the control beam (BK) is only 1,38% and 3,09%, consecutively. This increase is insignificant compared to those produced by other test specimens (Table 3). From observation during tests, the two beams failed prematurely due to the imperfectness of bond development between FRP sheets and concrete surface. Because the increase in shear capacity of the beams is insignificant then the test results of the two beams can be categorized as “outlier”.

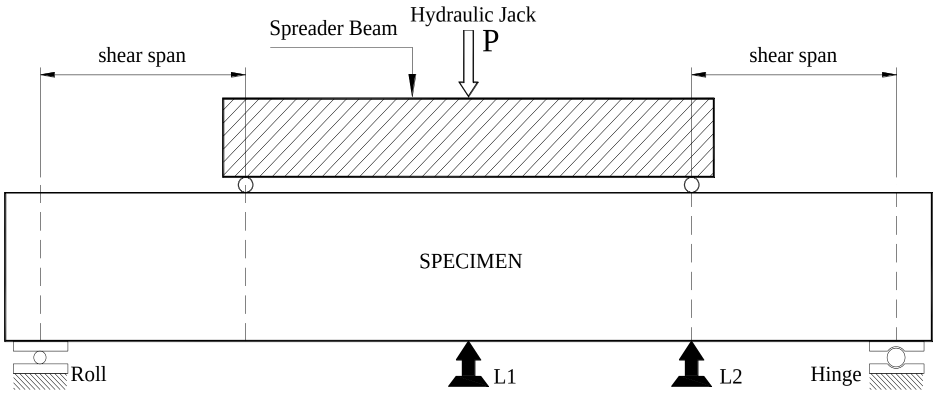


Figure 4: Test setup of beam specimens

Shear capacity of test specimens S40-D30S and U60-D40S consists of contribution from steel stirrups and from FRP stirrups. Analytically, the contribution of steel stirrups in carrying shear force on test beams S40-D30S and U60-D40S is 20.47 kN. With this, the contribution of FRP stirrups in carrying the shear force on test beams S40-D30S and U60-D40S is 20.67 kN and 36.93 kN, consecutively. In other words, there is an increase of 21.91% and 39.15% in shear capacity in those test beams, consecutively.

Based on the above results, the increase in shear capacity of test beam S40-D30S is basically not significant compared to that produced by the test beam without anchor, i.e. S40-TA. From observation on the test specimen, it was found that the length of FRP sheet on test specimen S40 – D30S was not adequate such that the ends of the FRP stirrups did not reach the top and bottom edges of the beam. As a result, the anchorage produced at the ends of the FRP stirrups did not work properly.

Table 3 also shows that the increase in shear capacity of test beams strengthened with 2-sided wrap scheme, i.e. S40-AC, S40-D30, S40-D30S and S40-TA, is 33.51%, 24.08%, 21.91% and 20.21% consecutively. Thus, test beams S40-AC, S40-D30 and S40-D30S showed an increase of 11.06%, 3.22%, and 1.41%, consecutively, in shear capacity compared to the shear capacity of the test beam without anchor (i.e. S40-TA). From these results, it can be seen that from all test beams strengthened with 2-sided wrap scheme, the test beams with the **C**-embedded anchor, i.e. S40-AC, produced the largest increase in shear capacity.

Test beams with insert anchor having head diameter of 40 mm, i.e. U60-D40S, and with **C**-embedded anchor, i.e. U60-AC, showed an increase in shear capacity of 36,93 kN (39,15%) and 47,49 kN (50,35%), respectively, with respect to the shear capacity of the control beam (Table 3). This indicates that from all the test beams strengthened with U-wrap scheme, the test beam with **C**-embedded anchor, i.e. U60-AC, had better performance in increasing shear capacity of the beams compared to the test beam with insert anchor. It is also indicated in Table 3 that the test beams with larger head diameter of insert anchor produced greater increase in shear capacity. This is probably due to the fact that larger head diameter will produce larger contact area with the FRP anchored end. This, in turn, will induce larger resistance toward debonding.

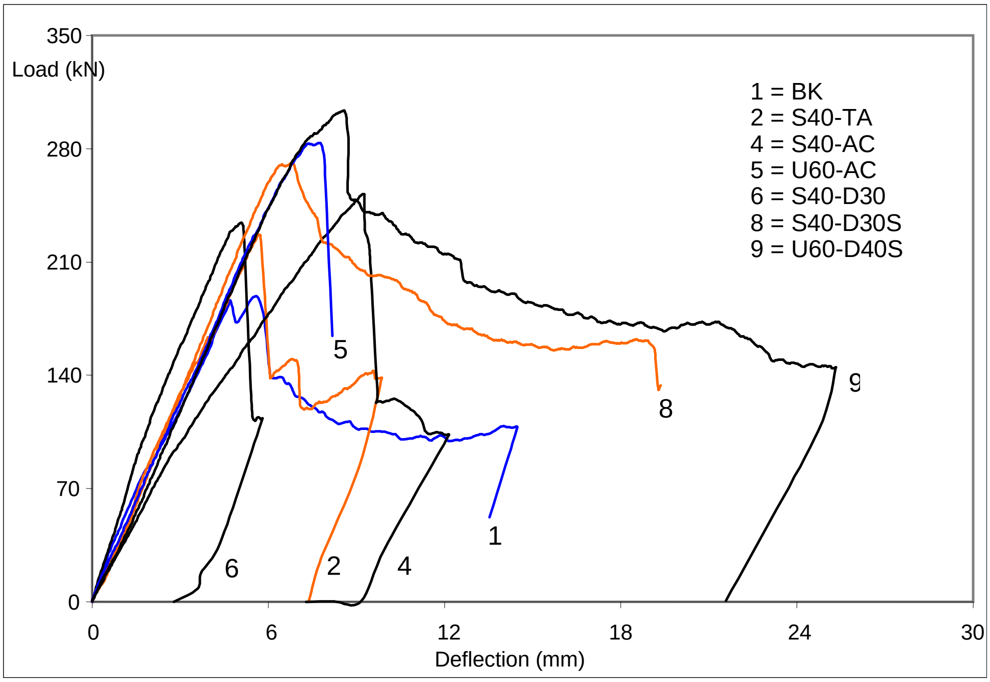
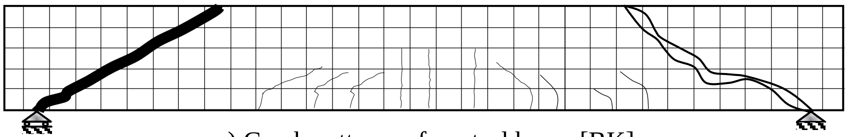


Figure 5: Load versus deflection relationship

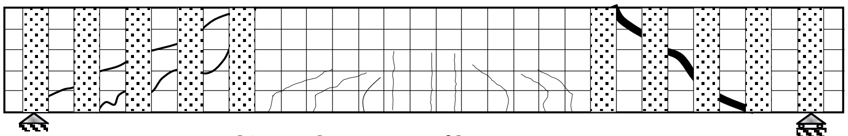
Table 3: Shear capacity of test beams (V_n)

No	Sample Code	Max Load P_{max} (kN)	Shear Capacity V_n (kN)	Shear Increase %	Deflection (mm)	Failure Mode
1	BK	188.61	94.31	-	5.53	Shear
2	S40-TA	226.74	113.37	20.21	5.67	Shear
3	U60-TA	191.23	95.62	1.38	5.13	Shear
4	S40-AC	251.83	125.92	33.51	9.22	Shear
5	U60-AC	283.59	141.80	50.35	7.70	Shear
6	S40-D30	234.03	117.02	24.08	5.05	Shear
7	U60-D40	194.44	97.22	3.09	5.11	Shear
8	S40-D30S	270.88	135.44	43.62(21.91) [1)]	6.77	Shear
9	U60-D40S	303.40	151.70	60.86(39.15) [1)]	7.16	Shear

[1)] Numbers in bracket are the increase in shear capacity due to FRP stirrups contribution

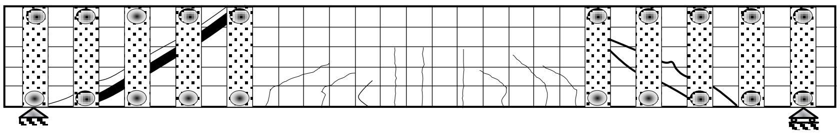


a) Crack patterns of control beam [BK]

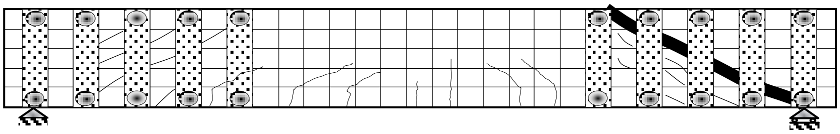


b) Crack patterns of beam S40-TA

c) Crack patterns of beam U60-AC



d) Crack patterns of beam S40-D30



e) Crack patterns of beam S40-D30S

Figure 6: Typical crack patterns in the beam specimens

3.4 Crack Patterns and Mode of Failure

In general, cracks were initiated at beams as flexural cracks. These cracks then propagated to form diagonal tensile cracks in the shear span area (Fig. 6). At failure, a major diagonal tensile crack was formed in the shear span at each beam. This major crack connected the loading point with the support region, as shown in Figure 7. The formation of this crack in all test beams indicates that all the test beams experienced diagonal shear failure as expected.

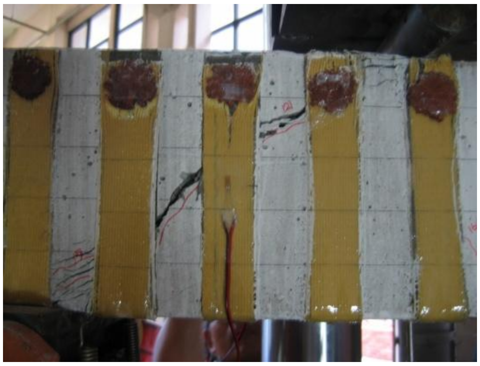


Figure 7: Diagonal crack crossing the FRP stirrups

3.5 Maximum Strain of FRP Stirrups

Table 4 shows the measured value of maximum strain of FRP stirrups. The average maximum strain value obtained from the tests was 0.0065. This strain corresponds to 36,9 % of ultimate strain of the AFRP sheets (Table 1). The largest measured maximum strain of FRP stirrups, i.e. 0.00775, was observed on test specimen U60-AC, which is a test specimen with **C**-embedded type of anchor. This result indicates that the **C**-embedded anchor was effective in increasing the contribution of FRP stirrups in carrying the shear force in the FRP shear strengthened concrete beams.

4.0 Analysis of FRP Contribution on the Shear Capacity of Beams

According to ACI Committee 440 (2002), the nominal shear strength of an FRP strengthened concrete member can be determined as follow:

$$\phi V_n = \phi(V_c + V_s + \psi_f V_f)$$

where:

V_c	is nominal shear strength provided by concrete
V_s	is nominal shear strength provided by steel stirrups
V_f	is nominal shear strength provided by FRP stirrups
ψ_f	is additional FRP-strength reduction factor

Table 4: Maximum strain of FRP stirrups

No.	Sample Code	Strain	
		Maximum Strain	Effective Strain Ratio[1] (%)
1	S40-AC	0,00675	37,5
2	U60-AC	0,00775	43,1
3	S40-D30	0,00722	40,1
4	U60-D40S	0,00488	27,1
Average		0,00665	36,9

[1]Ratio of measured maximum strain to ultimate strain of FRP stirrups

The shear strength contribution of FRP stirrups can be computed as follows (Fig. 8):

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_f}{s_f} \tag{2}$$

where :

A_{fv}	is area of FRP stirrups, $2*n*t_f*w_f$
n	is number of plies of FRP sheets
t_f	is thickness of one ply of FRP sheets
w_f	is width of FRP sheets
f_{fe}	is effective tensile stress of FRP sheets, $\varepsilon_{fe} * E_f$
ε_{fe}	is effective strain of FRP sheets
E_f	is modulus of elasticity of FRP sheets
d_f	is effective depth of FRP strengthened cross section
s_f	is spacing between FRP stirrups
α	is angle between FRP orientation and member axis ($\alpha = 90^o$ for this study)

The effective strain of the FRP sheets is the maximum strain that can be achieved in the FRP stirrups at ultimate load. This value is governed by the failure mode of the FRP strengthening system. ACI 440 (2002) defines the value of the effective strain of FRP stirrups at ultimate to be depend on the wrapping schemes used and limits the value to a maximum of 0.004.

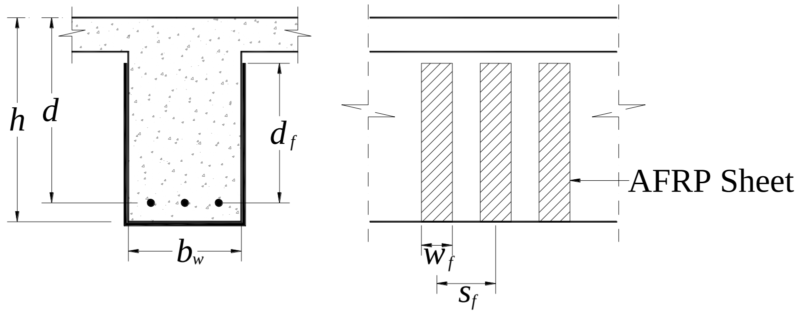


Figure 8: Dimensional variables for FRP-based shear strengthening

For reinforced concrete member strengthened using full-wrap scheme, loss of aggregate interlock of the concrete is observed to occur at fiber strains much less than the ultimate strain. To preclude this mode of failure, ACI 440 (2002) limits the maximum strain used for design to 0.4%, i.e.:

$$\varepsilon_{fe} = 0.004 \leq 0.75\ \varepsilon_{fu}$$

Two-sided wrap and U-wrap schemes have been observed to delaminate from the concrete before loss of aggregate interlock of the section. Thus, the effective strain is calculated by taking into account bond reduction coefficient, κ_v, (ACI 440, 2002), i.e.:

$$\varepsilon_{fe} = \kappa_v\ \varepsilon_{fu} \leq 0.004$$

Bond reduction coefficient is the function of the concrete strength, the type of wrapping scheme used, and the stiffness of the FRP sheets (ACI 440, 2002). The bond reduction coefficient can be computed from the following equations:

$$\kappa_v = \frac{k_1 k_2 L_e}{11900 * \varepsilon_{fu}} \leq 0.75 \tag{3}$$

The active bond length L_e is the length over which the majority of the bond stress is maintained. This length is given by following equations:

$$L_e = \frac{23300}{(n * t_f * E_f)^{0.58}} \tag{4}$$

$$k_1 = \left(\frac{fc'}{27} \right)^{2/3} \tag{5}$$

$$k_2 = \frac{d_f - L_e}{d_f} \quad \text{for U-wraps} \tag{6}$$

$$k_2 = \frac{d_f - 2L_e}{d_f} \quad \text{for 2-sided wraps} \tag{7}$$

Table 5 shows the comparison of shear contribution of FRP stirrups between experimental and analytical results. The ACI 440 equations (Eqns. 1 through 7) were used in the analytical results. The computation using the ACI 440 equations were performed three times, i.e. 1) By ignoring the anchorage system, 2) By assuming that the anchored stirrups have the same performance as the the full-wrap system, 3) By setting the effective strain to be 0.006.

Table 5: Comparison of test and computed results

No.	Sample Code	Shear Capacity V_n [kN]	Shear Contribution of FRP Stirrups, V_f [kN]			
			Test Results	ACI 440 (ignoring anchorage system)	ACI 440* (full wrap assumed)	ACI 440 (effective strain set at 0.006)
1	BK	94.31	-	-	-	-
2	S40-TA	113.37	19.07	6.80	-	-
3	S40-AC	125.92	31.61	6.80	16.21	24.32
4	U60-AC	141.80	47.49	24.02	24.02	36.04
5	S40-D30	117.02	22.71	6.80	16.21	24.32
6	S40-D30S	135.44	20.67	6.80	16.21	24.32
7	U60-D40S	151.70	36.93	24.02	24.02	36.04

*maximum effective strain is limited to 0.004

It can be seen from the table that adopting the ACI 440 equations for each respective wrapping scheme, and ignoring the anchorage system applied, results in unreasonably lower estimate of FRP shear contribution. By adopting the equations for full wrap system, the estimate value is closer to the experimental results. The closest estimate from the analytical results is given by the analysis which assume that the effective strain on the FRP stirrups can reach 0.006.

5.0 Conclusion

This paper presents experimental and analytical study for evaluating contribution of FRP stirrups with anchored ends in resisting shear forces of shear strengthened reinforced concrete beams. Anchorage systems proposed in this study are insert anchor system and **C-**embedded anchor system. Based on the results of this study, it can be concluded that:

1. The performance of FRP shear strengthened concrete members is very dependent on the quality of FRP installation on the concrete member.
2. Shear strengthening methods using FRP stirrups with anchored ends were found to be effective in increasing contribution of FRP stirrups in resisting shear force in shear strengthened reinforced concrete beams. The **C**-embedded anchor system showed better performance than the insert anchor system.
3. The use of larger head diameter for the insert anchor produced larger shear capacity in the beams. This shows that the matrix applied in between FRP sheets and the contact surface of the head of the insert anchor influenced the shear capacity of the beams.
4. Effective average strain of the FRP stirrups was found to be 0.00665. This measured strain is larger than the maximum strain allowed by ACI Committee 440 (2002) for design, i.e. 0.004. This result indicates that the anchorage system proposed is effective in enhancing the bond capacity between FRP sheets and concrete surface.
5. The design equations for full-wrap system can be adopted for the design of reinforced concrete beams strengthened using FRP stirrups with anchored ends.

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