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ACI guidelines to assess the performance of CFRP-strengthened concrete beams with transverse end U wraps

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Abstract: In this comprehensive study, firstly, the theoretical model described in ACI 440 committee report to calculate the area of transverse U wraps provided for anchored CFRP-strengthened concrete beams was examined. Then, an experimental study was carried out with a total of 10 small-scale test specimens and test parameters were set to inspect the validity of the limitations given in the above theoretical model. Theoretical calculations were performed in accordance with ACI guidelines for the above test specimens as well as for the previous research studies. Finally, the constraints of applicability of the theoretical model given in ACI 440 committee report was discussed presenting new recommendations for different scenarios.

Keywords: CFRP, debonding, flexural capacity, transverse end U wraps

1. Introduction

Impacts of environmental degradation due to numerous ageing mechanisms, accidental damage and increased loading decline structural integrity and prolonged service life of reinforced concrete (RC) structures. The use of Carbon Fiber Reinforced Polymers (CFRPs) to rehabilitate the RC structures has become more popular among conventional strengthening methods such as external pre-stressing, the use of externally bonded steel plates and section enlargement [1, 2]. This can be mainly attributed to its excellent material characteristics such as light weight, high tensile strength, durability, low maintenance and ease of installation.

However, inherent deficiencies have reduced the effectiveness of CFRP systems due to the occurrence of premature failure modes causing structures to fail at much lower loads than expected. These debonding failure modes are typically caused by the loss of composite action between the concrete and CFRP [3]. FRP debonding generally initiates within the bond line due to high interfacial stress concentrations and results in primarily two types of failures [4, 5]. The first type is “mid-span debonding”, which may initiate at flexural or shear cracks close to the mid-span and then propagates towards the plate end. Debonding may also occur near the plate end and this type is identified as “end debonding”. This type of failure commonly exhibits crack propagation in the direction of mid-span caused by a predominant shear crack induced at the plate end [4, 5].

The provision of anchorages for externally bonded CFRP laminates to soffits is identified as a promising technique to prevent or delay premature debonding failures and thereby greatly improves the failure loads of CFRP-concrete systems [6, 7]. To enhance the flexural performance of CFRP-strengthened concrete beams, numerous research studies have been focused on the use of end anchorages in the form of transverse FRP end U wraps. These research studies concluded that the provision of transverse FRP end U wraps not only increases the failure loads, but also improves the ductility of CFRP/concrete composite beams.

Although provision of transverse FRP end U-wraps has proven its efficiency as a promising technique to delay premature end debonding failure, to the best of the authors’ knowledge, there are no well-documented guidelines to assess the performance of CFRP-concrete beams anchored with transverse end U-wraps. As a result, the extensive use of anchorage systems in the form of end U-wraps has been restricted. Xiang *et al.* [8] proposed a new theoretical model to calculate the moment capacity of anchored CFRP/concrete beams with transverse end U-wraps which is only applicable for low-strength concrete beams.

In the ACI 440 Committee report [9] for externally bonded FRP systems, Section 10.1.1 in chapter 10 and section 13.1.2 in chapter 13 emphasize the importance of provision of transverse FRP U-wraps which offer a clamping effect against cover separation failure for the improved bond behaviour of CFRP-strengthened concrete beams. Moreover, a set of equations is presented to compute the area of transverse clamping of FRP U-wraps to prevent concrete cover separation failure, as proposed by Reed et al, 2005. Nevertheless, none of these equations estimate the resultant percentage strength gains compared to the provided anchorage area.

2. Literature review

Even though the provision of transverse U wraps, W wraps or L wraps to increase the shear capacity of CFRP-strengthened concrete beams has been comprehensively scrutinized and documented, few research studies have been focused on the influence of flexural capacity of CFRP-concrete composite beams due to the provision of transverse U wraps placed at the two ends of longitudinal CFRP laminate within the effective bond length. However, significant strength improvements have been observed in CFRP/concrete composite beams anchored with transverse end U wraps compared to non-anchored CFRP-strengthened concrete beams.

Buyle-Bodin & David [10] tested a 150 mm×300 mm×3000 mm size concrete beam strengthened using externally bonded 100 mm wide CFRP sheet anchored with two 300 mm wide transverse CFRP end U wraps and observed 33.58% strength gain compared to non-anchored CFRP-strengthened concrete control beam. Buyukozturk et al. [11] prepared two 150mm × 180mm × 1500mm concrete beams strengthened with 38 mm wide CFRP sheet bonded to the soffits and anchored with 80 mm and 160mm wide CFRP end U wraps. These specimens (S4PS1M & S4PS2M) were tested using four point bending test and observed failure loads were 205.8kN and 231.3kN, which is equivalent to 22.14% and 37.27% strength increments over non-anchored CFRP/concrete control composite beam. Ceroni [12] tested one CFRP-strengthened concrete beam with dimensions 100 mm×180 mm×2000 mm strengthened using 100 mm wide externally bonded CFRP sheet together with 100 mm transverse CFRP U wraps. The reported failure load was 41.3 kN with 10.43% strength increment compared to CFRP-strengthened beam without end U wraps. Pham & Al-Mahaidi [13] observed significant strength gains of 57.50% and 81.17% for concrete beams of 140 mm×260 mm×2900 mm dimensions strengthened with 100 mm wide CFRP laminates and anchored with 50 mm and 150 mm wide transverse end U wraps. These test specimens (A1a and A1b) were subjected to four point bending test and the above strength improvements were reported with respect to non-anchored CFRP/concrete control beam (E3b2). Pimanmas & Pornpongsaroj [14] prepared two CFPR/concrete beams with 120 mm×220 mm×2200 mm dimensions strengthened with 100mm wide CFRP sheets. These test specimens, A-420-U and B-200-U were anchored with 300 mm wide transverse CFRP U wraps and achieved 41.41% and 24.90% strength gains compared to CFRP-strengthened control beam. Anchored test specimens, CU2-d/2 and CU2-d with 80mm and 160 mm wide GFRP end U wraps were prepared by Sadrmomtazi et al. [15] and observed strength gains of 5.02% and 11.88% respectively in comparison to non-anchored CFRP/concrete beams. Smith & Teng [16] prepared two CFRP-strengthened concrete beams (4A & 5B) with 75 mm and 125 mm wide transverse end U wraps. The longitudinal CFRP sheet has 150 mm width which is bonded externally to the soffits of the beams. These test specimens were subjected to three point bending test and reported strength increments were 19.44% and 15.86% for 4A and 5B respectively. Sobuz et al. [17] tested one 150 mm×200 mm×2000 mm CFRP-strengthened concrete beam with 100 mm wide transverse CFRP end U wraps and observed 22.50% strength improvement over CFRP/concrete composite control beams. According to the experimental studies carried out by Valcuende et al. [18], they observed 8.24% increment in failure loads for anchored CFRP/concrete beams (with 300 mm wide CFRP U wraps) with respect to control concrete beams strengthened with 50 mm wide CFRP laminates. The dimensions of concrete beams were 100 mm×150 mm×1200 mm. Valivonis & Skuturna [19] used 100 mm wide end U wraps to anchor externally bonded CFRP/concrete beams with 100 mm wide CFRP laminate. They observed a significant strength increment of 40.02% due to the addition of transverse end U wraps.

3. ACI guidelines for anchored beams with transvers end U wraps

As stated in ACI 440 committee report [9], provision of transverse clamping FRP U-wraps along the length of the flexural FRP reinforcement has been observed to result in increased FRP strain at debonding. Thus, higher loads can be transferred to the flexural FRP laminates by utilizing material properties effectively, which in turn improves the overall efficiency of the strengthening system. The area of the transverse clamping CFRP U-wrap,

$A_{f\,anchor}$ can be computed in accordance with Eq. 13-1 given in the ACI 440 Committee report [9].

$$(A_f)_{anchor} = \frac{(A_f f_{fu})_{longitudinal}}{(E_f k_v \varepsilon_{fu})_{anchor}} \quad (1)$$

The bond reduction coefficient k_v depends upon the concrete strength, the type of wrapping scheme and the stiffness of the laminate. Thus, k_v can be calculated from Eq. 11-7 to 11-10, as stated in the ACI guidelines.

$$k_v = (k_1 k_2 L_e)/11{,}900\, \varepsilon_{fu} \leq 0.75 \quad (2)$$

The active bond length L_e is the length over which the majority of the bond stress is maintained. L_e can be obtained by Eq. 3.

$$L_e = 23{,}300/(n t_f E_f)^{0.58} \quad (3)$$

k_v depends on two other modification factors k_1 (Eq. (4) and k_2 (Eq. (5):

$$k_1 = (f_c'/27)^{\frac{2}{3}} \quad (4)$$

$$k_2 = \left(d_{fv} - L_e\right)/d_{fv} \quad for\ U\ wraps \quad (5)$$

Where f_c' is compressive strength on concrete and d_{fv} is height of the U wrap above tensile reinforcement bars as illustrated in Figure 1(a). As a result, if the height of end U wraps are lesser than a_s, Equation (5) is inapplicable and hence cannot compute the theoretical area of U wraps. Thus, according to the above theoretical model, transverse end U wraps should have a minimum height greater than a_s to be effective in delaying premature debonding failure. To examine the applicability of this constraint in terms of minimum height of the U wraps, an experimental programme was devised to inspect the influence of height of the transverse end U wraps. Even though addition of end U wraps which provides enhanced performances, in practice for rehabilitation, it may be difficult to bond transverse end U wraps with greater heights due to external barriers. In addition, provision of U wraps with greater heights does not always offer economical solutions due to lack of material efficiency. Thus, one objective of the test programme was to evaluate the strength gains correspond to shorter U wrap heights which is not specified in ACI guidelines. The test programme comprised both transverse FRP end U wrap configurations illustrated in Figure 1(a) and Figure 1(b). As shown in Figure 1(b), the provided height

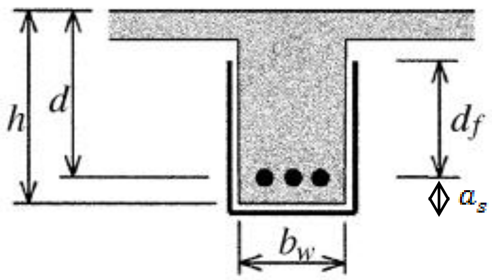


Figure 1(a) : Configuration of transverse end U wraps according to ACI report [9]

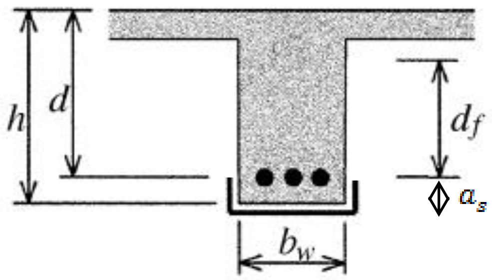


Figure 1(b) : Configuration of transverse end U wraps used in present test programme

of the U wrap was lesser than d_f as defined in Figure 1(a). For both end U wrap configurations, corresponding strength improvements were observed with respect to the provided height of end U wraps.

4. Test programme

To assess the validity of limitations considered in the theoretical model described in previous section, authors carried out an experimental study with a total of 10 numbers of small-scale reinforced concrete test specimens with dimensions 100 mm × 150mm × 750 mm (width × depth × length). The strengthening scheme of CFRP-strengthened test beams anchored with transverse FRP end U wraps is illustrated in Table 1. The test specimens were cast using grade 30 concrete mix with a maximum aggregate size of 20 mm and a water-cement ratio of 0.55. Standard size concrete cubes of 150 mm × 150 mm × 150 mm were also prepared and cured under similar laboratory conditions and measured average compressive strengths was 31.99 N/mm^2. Mild steel bars of 6 mm in diameter were used as the longitudinal reinforcement and galvanized iron bars of 4 mm in diameter were used to prepare shear links. The tensile strengths of 250 N/mm^2 and 363 N/mm^2 were obtained for mild steel and galvanized steel respectively using standard laboratory tests. Both CFRP and glass fibre reinforced polymer (GFRP) sheets were used for specimen preparation. A commercially available two-part epoxy adhesive was used to bond the FRP sheets. The material properties of both FRP sheets and the epoxy adhesive are listed in Table 2, in accordance with the manufacturers' specifications [20].

Table 1: Strengthening scheme of test specimens

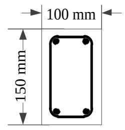
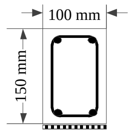
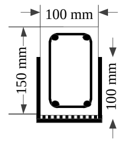
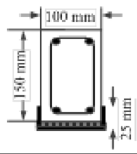
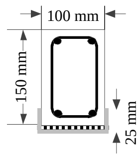
Designation	Description	Strengthening scheme	Figures
B/2/CC	Non-strengthened control concrete beam	None	
B/2/CF	CFRP-strengthened concrete beam	Strengthened with one externally bonded 100mm×600mm CFRP sheet	
B/2/CF$_{50}$	Anchored beams with CFRP U wraps	Strengthened with one externally bonded 100mm×600mm CFRP sheet + 50 mm wide two CFRP end U wraps	
B/2/CF$_{100}$	Anchored beams with CFRP U wraps	Strengthened with one externally bonded 100mm×600mm CFRP sheet + 100 mm wide two CFRP end U wraps	
B/2/GF$_{100}$	Anchored beams with GFRP U wraps	Strengthened with one externally bonded 100mm×600mm CFRP sheet + 100 mm wide two GFRP end U wraps	

Table 2: Material properties of FRP and two part epoxy adhesive [20]

FRP sheet			Two-part epoxy adhesive		
Parameters	CFRP	GFRP	Parameters	Primer	Saturant
Fibre Density (g/cm^3)	2.1	2.6	Yield Strength(MPa)	24.1	138
Fibre Modulus (GPa)	640	73	Strain at Yield (%)	4%	3.8%
Thickness (mm)	0.19	0.31	Elastic Modulus(MPa)	595	3724
Ultimate Tensile Strength (MPa)	2600	2400	Ultimate Strength(MPa)	24.1	138
Ultimate Tensile Elongation (%)	0.4	4.5	Glass Transition Temperature (°C)	77	71

The bottom surfaces of the concrete beams were sand-blasted prior to bonding of the FRP and resulted concrete substrates were reasonably rough. The wet lay-up system [9] was used to bond CFRP sheets onto the concrete beams. Primer part A (hardener) and part B (base) were mixed at 1:2 ratio by weight and a thin layer of primer was applied immediately after cleaning which resulted in a dry and slightly sticky film. The prepared concrete beams were set aside for about 45 minutes. The result was a dry, non-sticky surface that could be protected from contamination until epoxy adhesive was ready to be bonded to the substrate. Saturant part A (hardener) and part B

(base) were mixed using a 1:2 ratio by weight as per the manufacturer's specifications [20]. Next, the prepared concrete substrates and FRP sheets were saturated with epoxy saturant. CFRP sheets with dimensions of 100 mm × 600 mm impregnated with saturant were pressed onto the

concrete substrates and a ribbed roller was used to remove air entrapped in the bond line. Ribbed rolling was carried out in the direction parallel to the fibres. The epoxy adhesive had a pot life of 40 minutes and it was cured for 7 days at room temperature [20]. All CFPR-strengthened concrete control test beams were prepared following the above procedure.
The prepared test specimens were simply supported and subjected to three-point bending using an Amsler testing machine. Roller supports were placed 75 mm from the bonded CFRP sheet. A point load was applied at the top of the beam at mid-span. Mid-span deflections were recorded using a dial gauge and initiation of cracks was observed. The test specimens were further loaded to determine the corresponding failure modes. The average failure loads of non-strengthened concrete control beams were 14.71 kN.

5. Test results

The highest strength gain of 14.64% was found for the CFRP-concrete test beams with 100 mm wide CFRP U wraps ($B/2a/CF_{100}$), compared with the non-anchored CFRP-strengthened control beams (B/2a/CF). The resultant failure behaviour of test beams $B/2a/CF_{100}$ comprised separation of the concrete cover along the steel reinforcements. However, the test beams anchored with GFRP U wraps with a similar width ($B/2a/GF_{100}$) achieved only a 2.44% strength gain compared to the non-anchored CFRP-strengthened control beams. This was mainly due to the inappropriate thickness of the GFRP fibres, which hindered complete impregnation with epoxy adhesive, resulting in a poor bond between the longitudinal CFRP sheet and the transverse GFRP U wraps. A major shear crack was initiated at the end of CFRP sheet followed by delamination of the longitudinal CFRP sheet. A similar strength gain was achieved by anchored CFRP-strengthened specimens with 50 mm CFRP U wraps ($B/2a/CF_{50}$) and the resultant failure mode consisted of shear cracks at the innermost edge of the CFRP U wrap. All non-anchored CFRP-strengthened control beams failed due to cover separation failure and all non-strengthened control beams failed due to a single flexural crack initiated at mid-span. Although the implemented U wrap configurations were ineffective in delaying end debonding failure, type $B/2a/CF_{100}$ successfully achieved a noticeable strength gain.

6. Predictions from ACI guidelines

As explained in section 3, the theoretical area of transverse end U wraps were computed using Equations (1-5) for the test specimens in the present study as well as for the previous research studies reviewed in Section 2. The calculated areas of the end U-wraps are listed in Table 3. The theoretical widths of U-wraps, b_{ACI} were computed by dividing the calculated area of the transverse end U wrap by the total length of the U-wrap provided experimentally. As revealed in Table 3, most of the theoretical widths of U-wraps obtained from the ACI guidelines are considerably greater than the experimentally investigated widths of U wraps b_{exp} selected in this paper, although noticeable strength gains were reported.
Figure 2 shows the variation of percentage strength increments (compared to non-anchored CFRP-concrete beams) with the ratios of the theoretical widths of U-wraps over the experimental widths of U-wraps. As indicated in the graph, the behaviours of the above two parameters are quite scattered and hence it can be concluded that no strong relationship exists between these two parameters.

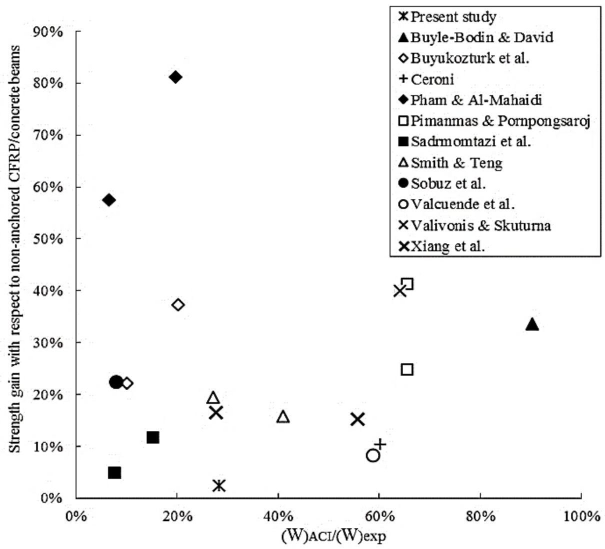


Figure 2: Variation of percentage strength increments (compared to non-anchored CFRP-concrete beams) with the ratios of theoretical width of U-wraps over experimental width of U-wraps

7. Conclusions and recommendations

CFRP-concrete composite beams exhibit several types of failure modes, of which premature end-debonding is the most critical type of failure, which takes place at the interface of the bond line or within the concrete cover zone. The provision of anchorages in the form of transverse end U wraps for externally bonded CFRP/concrete composites offers an excellent method of preventing or delaying premature debonding failure and thereby remarkably increasing the failure capacity of CFRP-concrete systems. As a result, higher loads can be transferred to the CFRP laminate, utilizing the material properties of CFRP more efficiently. However, the extensive use of FRP anchorage systems is restricted due to the lack of reliable design guidelines and also very few research studies have focused on enhancing the flexural capacity of CFRP-concrete composite beams using transverse U-wraps placed at both ends of the longitudinal CFRP laminate within the effective bond length. ACI 440 Committee report emphasizes the importance of provision of transverse FRP U-wraps to offer a clamping effect against cover separation failure for the improved bond behaviour of CFRP-strengthened concrete beams. A theoretical model is presented to compute the area of transverse clamping of FRP U-wraps to prevent concrete cover separation failure. Nevertheless, none of these equations estimate the resultant percentage strength gains compared to the provided anchorage area. According to the ACI theoretical model, transverse end U wraps should have a minimum height specified in the latter guideline to be effective in delaying premature debonding failure. In the present study, an experimental investigation was devised to examine the applicability of this constrain to inspect the influence of height of the transverse end U wraps. According to reported test results, anchored test beams with U wraps having shorter heights than minimum required heights defined in ACI guidelines also offered significant strength improvements with respect to non-anchored CFRP-strengthened control beams. Moreover, most of the theoretical widths of U-wraps obtained from the ACI guidelines are considerably greater than the experimentally provided widths of U wraps b_{exp}, although noticeable strength gain were reported from the previous experimental investigations in literature. Furthermore, it can be concluded that no strong relationship exists between the calculated theoretical area of U wraps and resulted strength improvements due to the provision of U wraps. Hence, the design guidelines should be reconsidered in order to design anchored CFRP/concrete beams with transverse end U wraps which also predict the corresponding strength gains to optimize the performance of CFRP/concrete composites in terms of material efficiency.

Table 3 : Theoretical and experimental areas of transverse end U wraps

Reference	Beam	$(A_f)_{anchor}$	L^*	W_{ACI}	W_{exp}	$\frac{W_{exp}}{W_{ACI}}$	Strength gain †
		mm^2	mm	mm	mm		%
Present study	B/2/CF$_{50}$	52905.41	300	176.4	50	28%	2.44%
	B/2/CF$_{100}$	N/A	150	N/A	100	N/A	14.64%
	B/2/GF$_{100}$	N/A	150	N/A	100	N/A	2.44%
Buyle-Bodin& David [10]	F	249212.56	750	332.3	300	90%	33.58%
Buyukozturk et al. [11]	S4PS1M	405089.50	510	794.3	80	10%	22.14%
	S4PS2M	405089.50	510	794.3	160	20%	37.27%
Ceroni [12]	A7	76477.27	460	166.3	100	60%	10.43%
Pham & Al-Mahaidi [13]	A1a	503205.43	660	762.4	50	7%	57.50%
	A1b	503205.43	660	762.4	150	20%	81.17%
Pimanmas & Pornpongsaroj [14]	A-420-U	256523.15	560	458.1	300	65%	41.41%
	B-200-U	256523.15	560	458.1	300	65%	24.90%
Sadrmomtazi et al.[15]	CU2-d/2	443806.76	420	1056.7	80	8%	5.02%
	CU2-d	443806.76	420	1056.7	160	15%	11.88%
Smith & Teng [16]	4A	179313.26	650	275.9	75	27%	19.44%
	5B	198263.11	650	305.0	125	41%	15.86%
Sobuz et al.[17]	FBF-1LU	691097.40	550	1256.5	100	8%	22.50%
Valcuende et al.[18]	B-SF	204514.08	400	511.3	300	59%	8.24%
Valivonis & Skuturna [19]	SD6	78053.69	500	156.1	100	64%	40.02%
Xiang et al. [8]	B12	201810.22	750	269.1	150	56%	15.17%
	B22	408825.01	753	542.9	150	28%	16.51%

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