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Theoretical and experimental assessment of the effect of adhesive bond thickness on the flexural capacity of CFRP strengthened beams

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ABSTRACT

Carbon Fiber Reinforced Polymer (CFRP) is a material of choice in the structural strengthening of reinforced concrete (RC) elements. In order to strengthen RC elements, CRFP is bonded externally to RC elements using adhesives. This paper investigates the effect of varying adhesive bond thickness on the moment capacity of CFRP strengthened RC beams in flexure. Thirty-eight (38) Reinforced concrete beams (1.2m length) were cast in the laboratory and their failure loads and corresponding moment capacities obtained when the adhesive bond thickness between the CFRP wraps and RC beams were varied. This paper examines the comparison between flexural moment capacities obtained experimentally and the predicted moment capacities using a theoretical procedure set out in AC440-2R-17 after structural strengthening with CFRP. It was observed that the adhesive thickness had a significant effect on the flexural capacity of strengthened beams. As the adhesive thickness increased beyond certain thresholds, the flexural capacity of strengthened beams reduced. At the optimum adhesive thickness threshold, the ACI 440-2r-17 procedures could predict to high accuracy the moment capacities of strengthened beams.

1. INTRODUCTION

Carbon Fiber Reinforced Polymer (CFRP) has become a material of choice in the structural strengthening of reinforced concrete (RC) elements (i.e., beams, slabs and columns). CFRP has also found its way into many other industries because of its superior performance when compared to steel. The lightweight, corrosion resistance and very high tensile strength of CFRP when compared to steel make it very desirable in structural retrofitting works in the civil engineering industry (Frhaan et al., 2021; Gholami et al., 2013). CFRP materials have played significant roles in the seismic strengthening and repair of deteriorated structures, especially bridges and other large civil engineering infrastructure (Pham & Nguyen, 2022).

The ACI 440 -2r- 17 (Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures) presents standard guidance for the design of CFRP strengthened concrete structures. There are other national guidelines for the design of CFRP strengthened RC structures, such as: UK Concrete Society Standard TR55; ISIS—Design Manual 4-FRP Rehabilitation of Reinforced Concrete Structures and AASHTO—Guide Specification for the Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements.

There are a couple of numerical studies that have investigated the behavior of CFRP strengthened elements, especially RC sections. Also, numerical finite element (FE) models have been used to validate experimental works on CFRP strengthening of RC elements (Bhavsar et al., 2022) . The shear and flexural strength of RC beams can be significantly improved by using externally bonded CFRP wraps(Mhanna et al., 2019). There have also been extensive experimental works to show that CFRP can strengthen steel beams (Katrizadeh & Narmashiri, 2019; Mhanna et al., 2019). In fact, it has been shown that CFRP layers can significantly improve the shear and flexural capacities of beams – even continuous beams (Abdallah et al., 2021). CFRP can be used as wraps and sheets when conducting structural retrofitting works (Abdallah et al., 2021; Selvapriya et al., 2022) . CFRP layers have also been shown to be very effective in strengthening prestressed concrete elements (Kang & Ary, 2012).

Several researchers have investigated the relationship between the estimated failure moment of resistance and the theoretical moment of resistance using theoretical calculations from the ACI (Alabdulhady et al., 2022). Other researchers have also studied the effect of bond thickness on the behavior of CFRP strengthened thin-walled steel beams (Szewczak et al., 2022). However, there are limited research works on the effect of adhesive thickness on the flexural capacity of CFRP strengthened RC beams in published literature.

Research has shown that the properties of adhesives play a significant role in the fracture energy of CFRP bonded structures(Wang et al., 2021) . For example, linear and brittle adhesives play significant roles in the stress distribution across adhesive layers between CFRP and RC concrete interface and thus impacts on the possibility of delamination(Wang et al., 2021). Previous research has shown, experimentally though, that there is a relationship between adhesive bond thickness and flexural strength of a CFRP strengthened RC beam (John A. TrustGod et al., 2022). This paper intends to investigate the relationship between the moment capacity obtained experimentally with that obtained from the ACI 440-2r-17 theoretical equations for a CFRP strengthened RC beam when adhesive bond thickness is varied. Though adhesive bond thickness could impact flexural moment capacity, ACI 440-2r-17 does not take into cognizance bond thickness in its theoretical equations. This paper also investigates the effect of changing the thickness of the CFRP layer on the experimentally obtained moment capacities of strengthened RC beams. This work presents a basis for optimizing the performance of CFRP strengthened structure. This research presents a guide to CFRP applicators in order to achieve optimum performance of a CFRP-RC beam interface. The optimization of thin layers of adhesive thickness in CFRP strengthening of RC beam elements has not been previously studied in existing literature.

2. METHOD

Thirty-eight (38) beams were cast with dimensions shown in Table 1 and Figure 1. The properties of the beams cast and the rebar used within the beams are shown in Table 2. The compressive strength of the test beams and the mechanical properties of the beams are shown in Table 1. The rebar configuration shown in Figure 1 and Table 1 were chosen in order to have a beam with a high shear capacity and in order to have flexural failure before shear failure.

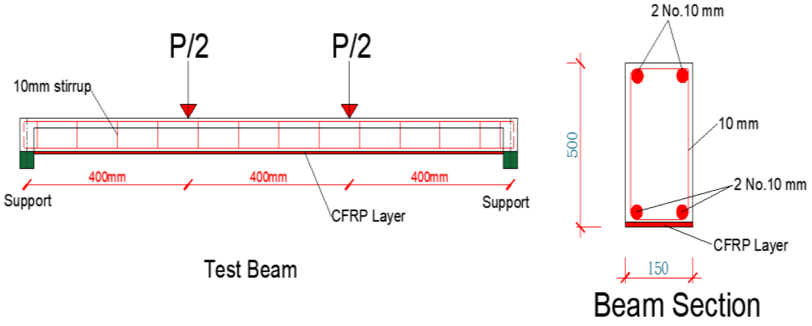

Figure 1. Experimental set-up for loading beams

Figure 2. Installation of CFRP wrap on the tension side of test beam

The tests beams were strengthened in flexure by bonding a layer of CFRP to their tension face, as shown in Figure 1. Each set of the test specimen comprises 6 beams, which were strengthened using various wraps of CFRP and adhesives. The various thickness of adhesives used to install the CFRP layer was measured using an electronic magnetic thickness gauge. Figure 2 shows the installation of CFRP fabric on the tension side of the test beam. The properties of CFRP wraps used for flexural strengthening are shown in Tables 3. The CFRP wraps were bought from Horse Construction China. Each of CFRP were cut into desired dimensions and were bonded to the cast RC beams using structural adhesives from Horse Construction China. The bonding adhesives were applied in such a manner that various thicknesses shown in Tables 3 to 5 were achieved with the help of hardeners. Three types of CFRP wraps were used in this experiment as shown in Tables 3 to 5- i.e., HM-30, HM-45 and HM-60. Figure 3 shows a pictural illustration of the wraps used in this study. After the application of adhesives, care was taken to ensure that there were no bubbles within the adhesives and that the desired thickness of adhesive impregnates the CFRP fabrics.

The mechanical properties of the CFRP wrap used to strengthen the three sets of beam cast are shown in Table 2. The Elastic Modulus of all CFRP wraps used is 259251 Mpa.

Table 1. Properties of RC test beam

Properties	**Values**
Height of Beam, h	500mm
Width of Beam, b	150mm
Concrete Compressive Strength, f_c (at 28 day)	30 MPa
Yield Strength of rebars, f_y	460MPa
Effective depth of centroid of tensile reinforcement, d	465mm
Effective depth of centroid of compressive reinforcement, d′	35mm
Area of rebars in the compressive zone, A'_s	158mm^2
Area of rebars in the tension zone,A_s	158mm^2
Area of transverse stirrup, A_v	158mm^2
Spacing of stirrups, s_v	100mm
Elastic modulus of rebars, E	200000 MPa

The mechanical properties of the CFRP wrap used to strengthen the three sets of beam cast are shown in Table 2. The Elastic Modulus of all CFRP wraps used is 259251 Mpa.

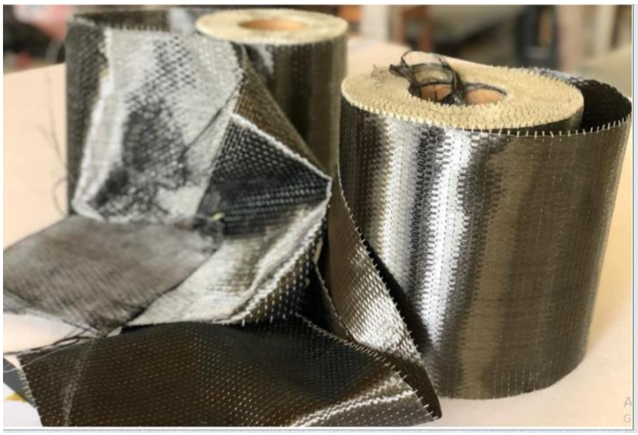

Figure 3. Pictorial representation of CFRP wraps used

Table 2. Mechanical properties of CFRP wraps (obtained from Manufacturer's data sheet)

Brand name	Specification	Thickness	Tensile Strength	Failure strain
HM -30	$300 g/m^2$	0.167mm	4084 MPa	0.0158
HM -45	$450 g/m^2$	0.25mm	4084 MPa	0.0158
HM -60	$600 g/m^2$	0.33mm	4084 MPa	0.0158

Table 3. Flexural strengthening with HM-30

Sample No.	Thickness of adhesive layer
A1	0.1mm
A2	0.15mm
A3	0.2mm
A4	0.25mm
A5	0.3mm
A6	0.35mm

Table 4. Flexural strengthening with HM-45

Sample No.	Thickness of adhesive layer
B1	0.1mm
B2	0.15mm
B3	0.2mm
B4	0.25mm
B5	0.3mm
B6	0.35mm

Table 3 shows the set of beams strengthened with HM-30 CFRP wraps, Table 4 shows the set of beams strengthened with HM -45 wraps and Table 5 shows the set of beams strengthened with HM-60. Each beam sample comprises 2 concrete cast beams. All beam samples shown in Tables 3 to 5 were subjected to a flexural test in the figuration shown in Figure 1. A set of two beams were taken as the control and were not strengthened with CFRP wraps.

Table 5. Flexural strengthening with HM-60

Sample No.	Thickness of adhesive layer
C1	0.1mm
C2	0.15mm
C3	0.2mm
C4	0.25mm
C5	0.3mm
C6	0.35mm

3. RESULTS AND DISCUSSION

The theoretical moment of resistance of the unstrengthened beams was obtained using ACI-318 stress-block principles shown in Figure 4 while the theoretical moment capacity of the strengthened beam was obtained using the procedure set-out by AC 440-2r-17. The beam was originally fabricated to have a high shear resistance so that the flexural failure is triggered before shear failure. Tables 6 and 7 show the theoretical calculation of the shear and flexural capacities of the test beam, respectively. The stress block in Figure 4 was used in Table 7.

For the details on the procedure for calculating the flexural capacity of strengthened RC beams, refer to (ACI 440.2R-17: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures on Apple Books, 2017).

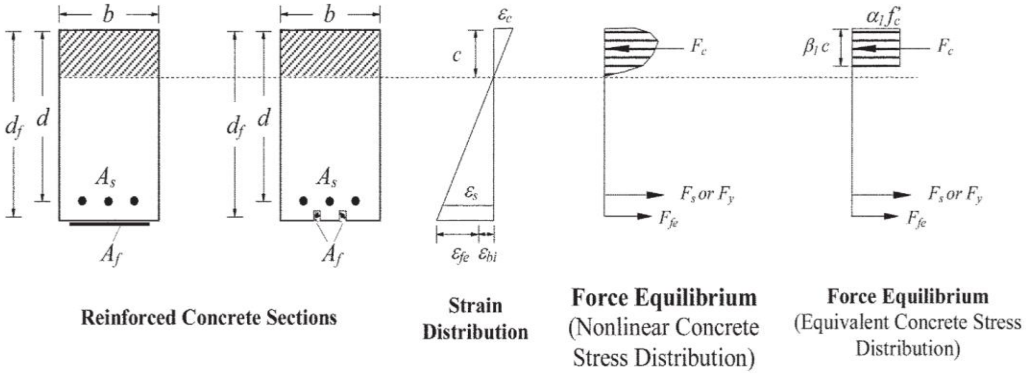

Figure 4. ACI 440 stress-block (ACI 440.2R-17: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures on Apple Books, 2017)

Table 6. Original shear capacity of test beam according to ACI 318

Shear contribution of concrete, V_c=0.17λ $f_c^{0.5}$ bd	**64.95kN**
Shear contribution of stirrups, $V_s=A_v f_{yt} d(\sin\alpha_t+\cos\alpha_t)/s_v$	335.99kN
Maximum spacing of shear reinforcement: s_{max}	116.5mm
Limit of shear capacity, V_{limit}=0.66 $f_c^{0.5}$ bd	252.14 kN
Thus, shear contribution of stirrups, V_s	252.14kN
Shear capacity of original beam, $V_n=V_c+V_s$	317.09kN
Strength reduction factor ϕ according to ACI 318R Table 21.2.1, ϕ:	0.75
Shear strength of original beam (i.e., factored shear capacity), $V_u=\phi V_n$=	237.81kN

Table 8 shows an example of the theoretical calculation of the increased flexural strength after strengthening with HM-60. The stress block in Figure 3 was used in Table 8. Also, the procedure illustrated in Table 8 was used to estimate the theoretical flexural strengthening of the test beams after strengthening with HM-45 and HM-60.

Table 7. Original flexural capacity of test beam according to ACI 318

Force in tensile steel, $F_s=A_s f_y$	**72.25kN**
Stress in compressive steel, $f_s'=f_y'-0.85f_c$	434.5MPa
Force in compressive steel, $C_s=A_s'f_s'$	68.25kN
Depth of compressive zone, x:	1.26mm
Compressive force in concrete, $C_c=0.85f_c b\beta_1 x$	4 kN
Equilibrium, $F_s=C_c+C_s$	68.25kN
Strain in compressive steel, $\varepsilon_s'=(x-d')\ \varepsilon_{cu}/x$	0.0805
Existing Flexural capacity, $M_n=C_c(d-\beta_1 x/2)+C_s\ (d-d')$	31.21kNm
Reduction factor, ϕ	0.9
Factored flexural capacity, $M_u=\phi\ M_n$	28.09kNm

Because of the depth and tensile stirrups used in the test beam, the flexural failure was triggered in test beams as test loads increased. Figure 5 shows the pictorial view of the flexural failure of the test beams.

Table 8. Flexural strengthening calculation according to ACI 440 2r-17

Tensile steel contribution to bending, $M_{ns}=A_sf_s(d-\beta_1x/2)$	**32.08 kNm**
Compressive steel contribution to bending, $M'_{ns}=A'_sf'_y(d'\beta_1x/2-d')$	-0.15 kNm
Area of CFRP, A_{fp}:	49.95mm^2
Stress in CFRP, $f_{fe}=E_f\varepsilon_{fe}$	1981.45
Ultimate tensile strength of the FRP material as reported by the manufacturer:	4084 MPa
Effective depth of centroid of CFRP, d_f :	500 mm
CFRP contribution to bending, $M_{nf}=A_{fp}f_{fe}(d_f-\beta_1x/2)$	47.41 kNm
Yield strain of steel: $\varepsilon_{sy}=\varepsilon_y=f_y/E_s=0.0023$	0.0023
$\Phi=$	0.9
$\Psi_f=$	0.85
Strengthened flexural strength, $\phi M_n=\phi(M_{ns}+M'_{ns}+\Psi_f M_{nf})$	65.01 kNm

Figure 5. Pictorial evidence of flexural failure of test beam

Tables 9 to 11 show the obtained flexural capacities from strengthening the cast beams with HM-30, HM-45 and HM-60 wraps, respectively.

Table 9. Theoretical estimation of increased capacity of RC beam strengthened with HM -30

Original Moment Capacity	**28.09 kNm**
Moment Capacity after Strengthening	54.84 kNm
Strengthening System	Material: HM-30 Number of layers: 1 Width of CFRP: 150 mm

Table 10. Theoretical estimation of increased capacity of RC beam strengthened with HM -45

Original Moment Capacity	**28.09 kNm**
Moment Capacity after Strengthening	60.37 kNm
Strengthening system	Material: HM-45 Number of layers: 1 Width of CFRP: 150 mm

Table 11. Theoretical estimation of increased capacity of RC beam strengthened with HM -60

Original Moment Capacity	**28.09 kNm**
Moment Capacity after Strengthening	65.01 kNm
Strengthening System	Material: HM-60 Number of layers: 1 Width of CFRP: 150 mm

Correspondingly, the bending moments at which flexural cracks were observed in the samples during flexural tests were obtained and compared to the flexural capacity obtained from theoretical ACI - 440-2r-17 procedures. For the control specimen, the flexural capacity obtained from experiment was 27.5kNm. For this control specimen sample, this value compares well with the 28.09kNm flexural moment capacity obtained from theoretical calculations as shown in Tables 7. It is also important to note that a maximum shear force of 162.5kN is obtained for a HM-60 strengthened beam when the theoretical flexural capacity is 65.01kNm. This value of shear force is less than the shear capacity of the unstrengthened beam which is estimated at 237.81kN as shown in Table 6. Thus, flexural failure was bound to be triggered before shear failure in the test beam set-up. As shown in Tables 12 to 14, the flexural capacities predicted by ACI's theoretical computation correlates well with strengthened beams whose adhesive thickness were in the thickness's neighborhood of the CFRP wrap. It is observed that beyond certain thicknesses, the moment capacities of strengthened beams decrease.

Table 12. Comparison between theoretical estimated capacity of CFRP strengthened beam and experimentally obtained Capacity (HM -30 strengthened beam)

Sample No.	Thickness of adhesive layer	Failure moment from flexural experiment	Theoretical moment capacity from ACI - 440-2r-17^{Note 1}	% error with reference to theoretical flexural moment capacity
A1	0.1mm	46 kNm	54.84 kNm	16.12%
A2	0.15mm	54 kNm	54.84 kNm	1.53%
A3	0.2mm	45 kNm	54.84 kNm	17.94%
A4	0.25mm	45 kNm	54.84 kNm	17.94%
A5	0.3mm	44 kNm	54.84 kNm	19.77%
A6	0.35mm	46 kNm	54.84 kNm	16.12%

Table 13. Comparison between theoretical estimated capacity of CFRP strengthened beam and experimentally obtained Capacity (HM -45 strengthened beam)

Sample No.	Thickness of adhesive layer	Failure Moment from flexural experiment	Theoretical Moment Capacity from ACI - 440-2r-17^{Note 1}	% error with reference to theoretical flexural moment capacity
B1	0.1mm	51 kNm	60.37 kNm	15.52%
B2	0.15mm	52 kNm	60.37 kNm	13.86%
B3	0.2mm	55 kNm	60.37 kNm	8.90%
B4	0.25mm	58 kNm	60.37 kNm	3.93%
B5	0.3mm	50 kNm	60.37 kNm	17.18%
B6	0.35mm	49 kNm	60.37 kNm	18.83%

Table 14. Comparison between theoretical estimated capacity of CFRP strengthened beam and experimentally obtained Capacity (HM -60 strengthened beam)

Sample No.	Thickness of adhesive layer	Failure moment from flexural experiment	Theoretical moment capacity from ACI - 440-2r-17^{Note 1}	% error with reference to theoretical flexural moment capacity
C1	0.1mm	58 kNm	65.01 kNm	10.78%
C2	0.15mm	58 kNm	65.01 kNm	10.78%
C3	0.2mm	55 kNm	65.01 kNm	15.40%
C4	0.25mm	57 kNm	65.01 kNm	12.32%
C5	0.3mm	64 kNm	65.01 kNm	1.55%
C6	0.35mm	55 kNm	65.01 kNm	15.4%

Note 1: ACI-440-2r-17 does not consider bond thickness in its calculations

Further comparison between the experimental and theoretical values of the flexural moment capacities of the strengthened beams in this work shows that at an adhesive thickness corresponding to the thickness of the CFRP fabric, the flexural strength obtained from experiment corresponds well with the flexural capacity predicted by the ACI -440-2r-17 theoretical model. For example, for beams strengthened with HM-30 shown in Table 12, HM-30 performed better as a strengthening medium with an adhesive layer thickness of 0.15mm which is approximately equal to the 0.167mm thickness of the HM-30. The same applies to HM-45 and HM-60 in Tables 13 and 14, respectively. This implies that an optimum flexural strength is achieved with adhesive thickness corresponding to the thickness of CFRP fabric. Outside this optimum adhesive thickness, the optimum flexural strength predicted by ACI -440-2r-17 could not be achieved by experiment. Thus, an optimum adhesive thickness corresponds to an adhesive thickness that can saturate the CFRP fabric in the CFRP-beam composite in order to improve the performance of the CFRP fabric as a strengthening medium. Also, it is important to note ACI -440-2r-17 does not consider the thickness of adhesive and other intrinsic behaviour of the adhesive in its mathematical model. This accounts for the constant values of theoretical flexural capacities obtained in Tables 12 to 14. However, this experiment has shown that improperly applied adhesives could impact flexural capacities of beams when compared to ACI -440-2r-17 theoretical model.

4. CONCLUSION

It is observed that the flexural strength or capacities of RC beams increased with increasing thickness of CFRP wraps when CFRP wraps are attached to the tensile side of the RC beam. Thus, the thickest CFRP wrap used in this experiment gave the highest moment capacity after strengthening of the RC beam. By wrapping the beams in the flexural zone of the RC for the whole length, significant increase in the flexural capacity of the RC beams were observed.

It is also observed that beyond a certain threshold adhesive thickness, the moment capacities of strengthened beams decreased. This implies that the thicknesses of the structural adhesives (i.e., the substance used to bond CFRP wraps to RC beams during strengthening) had significant impact in the moment capacity of the CFRP strengthened elements. At optimum adhesive thicknesses, the theoretical estimation of the moment capacity using ACI-440-2r-17 procedure correlated well with experimentally obtained moment capacities. From the experimental investigation in this research, the optimum thickness of adhesive layers was approximately equal to the thickness of the CFRP fabric. The thickness of CFRP wrap used in strengthening plays significant role in the increase in moment capacity achieved after strengthening. Thicker layers of CFRP wraps give higher moment capacities when flexural capacity increments are desired. This investigation shows that care should be taken when applying adhesives in the CFRP strengthening of beams. Using excessive adhesive layers when bonding CFRP to RC beams could be detrimental to the desired strength increment. It could also make the adhesive layer to be weak link in the composite action between CFRP and RC beam

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