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Effect of FRP-to-Concrete Interface Thickness on the Load Carrying Capacity of Reinforced Concrete Beams Strengthened Externally

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ABSTRACT: *This paper examines and describes the results of the effect of FRP to Concrete interface thickness on the load- carrying capacity of reinforced concrete beams strengthened externally. Five sets of reinforced concrete beam samples with 100x150x1100 mm dimensions, flexural internal reinforcement (As =2Φ10mm), and (AS1 =2Φ8mm) and shear reinforcement (Asv =Φ6mm @ 200mm c/c) were produced in the Civil Engineering laboratory. The first set of beams known as "A1" had no external reinforcement. The second set of beams known as" A2" were strengthened in flexure externally with 1mm thickness of Glass Fibre Fabrics (GFF) and 4mm bond thickness (Epoxy resin of Sikadur(R)-31) in the Tension Face (TF). The third set of beams known as" A3" were strengthened in flexure externally with 1mm thickness of GFF and 8mm bond thickness (Epoxy resin of Sikadur(R)-31) in the TF. The fourth set of beams known as" A4" were strengthened in flexure externally with 1.5mm thickness of GFF and 4mm bond thickness (Epoxy resin of Sikadur(R)-31) in the TF. The fifth set of beams known as" A5" were strengthened in flexure externally with 1.5mm thickness of GFF and 8mm bond thickness (Epoxy resin of Sikadur(R)-31) in the TF. From each set, three beams were produced. The surfaces of the beams were thoroughly roughed and cleaned, the GFF was placed on the tensile surface of the beams using the Epoxy resin of Sikadur(R)-31 as an adhesive substance and was left for a minimum curing period of 7days for effective bonding. All the beams were tested as simply supported beams under two-point loads.*

The study results confirmed that beam A2 achieved a higher ultimate load-carrying capacity than beam A3. Beam A2 and A3 was strengthened with the same FRP thickness of 1mm, and in comparison, beam A2 which was strengthened with 4mm concrete to FRP interface thickness (4mm Epoxy resin of Sikadur(R)-31 thickness) achieved a higher ultimate load-carrying capacity than beam A3 which were strengthened with 8mm concrete to FRP interface thickness (8mm Epoxy resin of Sikadur(R)-31 thickness). The increase in the load-carrying capacity for beam A2 is 7% relative to A3, Also beam A4 and A5 were strengthened with the same FRP thickness of 1.5mm, and in comparison, beam A5 which was strengthened with 8mm concrete to FRP interface thickness (8mm Epoxy resin of Sikadur(R)-31 thickness) attained a higher ultimate load-carrying capacity than beam A4 which was strengthened with 4mm concrete to FRP interface thickness (4mm Epoxy resin of Sikadur(R)-31 thickness) . The increase in the load-carrying capacity for beam A5 is 15% relative to A4. The study results also validate the comparison of beam A2 and beam A4, given that beam A2 and beam A4 were strengthened with the same 4mm concrete to FRP interface thickness (4mm Epoxy resin of Sikadur(R)-31 thickness), beam A2 which was strengthened externally with a FRP thickness of 1mm had a higher ultimate load-carrying capacity than beam A4 which was strengthened externally with a FRP thickness of 1.5mm. The increase in the ultimate load for beam A2 is 1.3% compared to A4, whereas beam A5 is 9% higher than beam A3. it is recommended, from the verified research results, that the FRP to concrete interface thickness should not exceed 5 times the FRP thickness

Keywords: *Interface thickness, Load- carrying capacity, FRP, Epoxy resin of Sikadur(R)-31, Crack Pattern,*

I. INTRODUCTION

The practice of external bonding of fiber-reinforced polymer (FRP) laminates in structural applications has

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emerged as a most recognized technique for the strengthening of reinforced concrete structural members [1-3]. FRP composite materials have densities varying from 1200 – 2100kg/m^3 [4], they are light in handling, have high tensile strength and together with their outstanding environmental durability have made them a contending option in contrast to the traditional strengthening materials. FRP repair and strengthening practices are widely used in present-day attributable to the development of design guidelines. In this strengthening practice, the behavior of the FRP-to-concrete interface and the interface thickness is of vital importance in providing a functional stress transfer. It has been publicized through both theoretical, numerical, and experimental investigations that FRP composites as external reinforcement with the aid of epoxy help to improve the load-carrying capacity, shear performance, and bending capacity of a structural member. Though the technique is yet to become a conventional practice, however, existing investigations have been primarily related to the performance of the system [5], but much less focus has been on the FRP-to-concrete interface thickness and woven fiber. In reinforced concrete beams strengthened externally for bending by bonded FRP sheet to the tension face, intermediate crack stimulated debonding (IC debonding) may emerge at a significant flexural crack or flexural-shear crack [6–8]. In reinforced concrete beams strengthened externally for shear with bonded FRP sheet to the sides, IC debonding can arise due to a shear crack [9]. The observed type of the main failure modes of externally strengthened reinforced concrete beams was differed in several experimental studies to date, for example, [10-14]. The existence of localized debonding at the position of flexural cracks usually does not affect the performance of the strengthening system, nevertheless, if the localized intermediate cracks smear and combine, such that the strain in the FRP decreases, then this phenomenon is known as Intermediate crack debonding of the strengthening system [15]. Ahmed et al., (2001) tested a series of reinforced concrete beams strengthened with CFRP laminates. The effect of the un-plated lengths as well as the amounts of externally bonded CFRP laminates upon the interfacial shear stress was studied [16]. Maalej and Bian (2001) tested five identical reinforced concrete beams strengthened by CFRP plate with different thickness and measured the interfacial shear stresses concentration at the plate curtailments. The effect of CFRP thickness on the shear stress concentration, failure modes, and strengthening efficiency ratio was studied [17]. The analytical results using [18]'s and [19]'s formulas were also presented to make a comparison with the experimental results. Bonacci and Maalej (2001) compiled an experimental database from the existing database, which includes a total of 127 specimens from 23 separate studies [20]. Mithaq et al (2013) investigated deflection control on R.C experimentally. The beam was reinforced externally with a carbon fiber reinforced polymer (CFRP) sheet. The investigation established that the external reinforcement of the CFRP sheet has a considerable effect on the load-deflection response by increasing the beam stiffness, particularly the super-pre-cracking phase [21]. Kamal et al (2019) study on retrofitting of reinforced concrete beams subjected to shear and flexure by various techniques. Two sets of four beams were researched on, one control beam for each set, and the other three beams were reinforced by different methods. The beams were tested under a four-point load. The performance of the reinforced beams was compared with RC beams without external reinforcement under shear and bending stresses. The study revealed that the bearing capacity of CFRP strengthened beams increases by 24% and 27% in terms of shear and bending stress acceptance, while the beams strengthened with steel fiber reinforced concrete SFRC have the lowest and did not meet the purpose of the study [22].

This paper examines the effect of FRP-to-concrete interface thickness on the load-carrying capacity of reinforced concrete beams strengthened externally. This research will establish optimal adhesive thickness and will serve as an engineering knowledge database for those involved in the performance, effectiveness, and cost of available strengthening materials. This is the focal point and knowledge gap aimed to be filled by the authors.

II. MATERIAL AND METHODS

Five sets of reinforced concrete beam samples with 100x150x1100 mm dimensions, flexural internal reinforcement (As =2Φ10mm) and (AS1 =2Φ8mm), and shear reinforcement (Asv =Φ6mm @ 200mm c/c) were produced in the Civil Engineering laboratory. The first set of beams known as "A1" had no external reinforcement (Glass fiber fabric). The second set of beams known as" A2" were strengthened in flexure externally with 1mm thickness of Glass Fibre Fabrics (GFF) and 4mm bond thickness (Epoxy resin of Sikadur$^{(R)}$-31) in the Tension Face (TF).

The third set of beams known as" A3" were strengthened in flexure externally with 1mm thickness of GFF and 8mm bond thickness (Epoxy resin of Sikadur(R)-31) in the TF. The fourth set of beams known as" A4" were strengthened in flexure externally with 1.5mm thickness of GFF and 4mm bond thickness (Epoxy resin of Sikadur(R)-31) in the TF. The fifth set of beams known as" A5" were strengthened in flexure externally with 1.5mm thickness of GFF and 8mm bond thickness (Epoxy resin of Sikadur(R)-31) in the TF. The specifications of the sample types are given in Table 1. From each set, three beams were produced. The strengthening process includes preparing the beams by roughing the surfaces of the beams to achieve a suitable face to have as much friction as attainable.

Table 1: Sample Types

Set of Beams	Interface Thickness (mm)	External Reinforcement thickness (mm)	Type of External Reinforcement	Number of Samples
A1	-	-	-	# 3
A2	4	1	GFF	# 3
A3	8	1	GFF	# 3
A4	4	1.5	GFF	# 3
A5	8	1.5	GFF	# 3

After the surfaces of the beams were thoroughly roughed and cleaned, the GFF was bond to the tensile surface of the beams using the Epoxy resin of Sikadur(R)-31 as an adhesive substance and was left for a minimum curing day for effective bonding. See Figure 1 for illustration. All the beams were tested as simply supported beams under two-point loads.

(a) (b) (c)

Fig. 1. Strengthening Process: (a) Roughing the Surfaces of the Beams (b) Mixing Adhesive Substance (c) Bonding of GFF to the tensile surface of the beam

III. RESULT

This section presents the study results of the effect of FRP-to-concrete interface thickness on the load-carrying capacity of reinforced concrete beams strengthened externally. Five sets of beams, A1, A2, A3, A4, and A5, were tested and the results of first crack and ultimate failure loads, deflection, and mode of failure were recorded and presented in Table 2, Figure 2 and 3.

Table 2: Experimental results

Sets of beams	First Crack Load, Pc (kN)	Deflection Dc(mm)	Ultimate Failure Load, Pu (kN)	Deflection Du(mm)	Failure Mode
A1	28.70	2.85	35.42	3.87	Flexural
A2	32.89	3.20	41.22	7.38	Shear
A3	31.69	4.00	38.47	6.70	Shear
A4	34.26	5.29	35.63	5.95	Shear
A5	39.47	4.26	42.13	6.55	Flexural

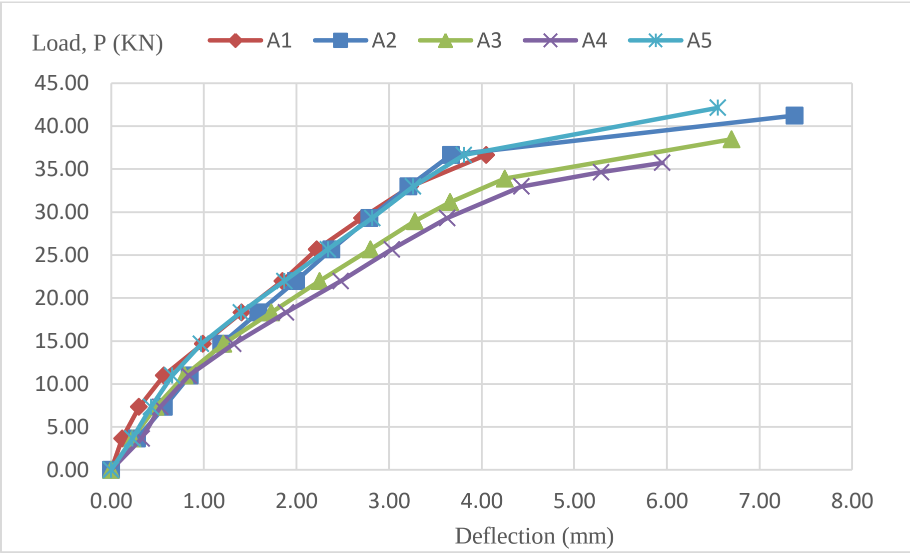

Fig. 2: load against deflection at mid-span

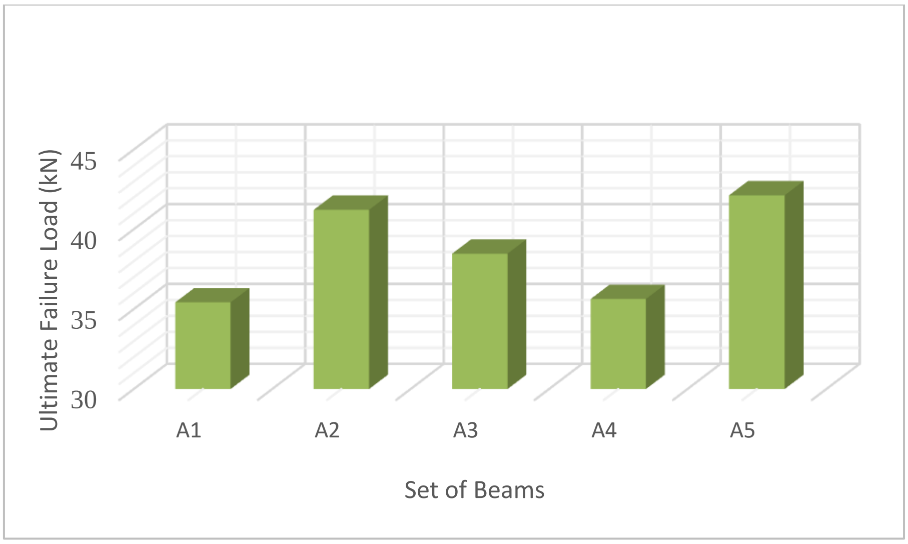

Fig. 3: Ultimate failure load (kN) of Sample Type

IV. DISCUSSION

This section describes the study results of the effect of FRP-to-concrete interface thickness on the load-carrying capacity of reinforced concrete beams strengthened externally. The results of first crack and ultimate failure loads, deflection and mode of failure were noted and presented in the result section.

Load Deflection Relationship

Figure 2 presents load against deflection at mid-span for five sets of beams, A1, A2, A3, A4, and A5 respectively. The study results of Figure 2 and Table 2 show that the maximum mid-span deflection of the control beam (A1) is 3.87mm at the ultimate failure load of 35.42kN, while the maximum mid-span deflection of beam A2 is 7.38mm at the ultimate failure load of 41.22kN. The maximum deflection of beam A3 at mid-span was 6.70mm at the failure load of 38.47kN. The failure mode of beam A1 was a flexural failure, whereas for beams A2 and A3 the failure mode was a shear failure. The maximum mid-span deflection for beam A4 is 5.95mm at the ultimate failure load of 33.63kN, and the failure mode was a shear failure perhaps cause by shear stresses, whereas the maximum mid-span deflection for beam A5 is 6.55 mm at the failure load of 42.13 kN and the failure was a flexural at the mid-span probably as a result of bending stresses.

Crack Pattern

The initial crack was noticed at a load of 28.70 kN for beam A1 and a load of 39.47 kN for beam A5. The first cracks crop up at around the mid-span of the beam. As the load step increases, the cracks become visible and propagated toward the compression plane. The beams A1 and A5 exhibited flexural failure. The first crack appeared near the right support of the beam at a load of 32.87kN, 31.69kN, and 34.26kN for beam A2, A3, and A4 respectively. The Beam A2, A3 and, A4 exhibited flexural shear cracks as the load step increases. The cracks started as flexural cracks and turn into Shear cracks as the load increases. The cracks were seemed to be perpendicular to principal tensile stresses. The results indicate that beam A2, A3, A4 and A5 with an externally reinforced FRP transferred the performance of the beam from ductile behavior to brittle failure.

Fig. 4. Failure Mode of Beam Samples: (a) Sample Type-A3, (b) Sample Type-A5, (c) Sample Type-A1, and (d) Type-A4

Effect of FRP-to-Concrete Interface Thickness

The study results confirmed that beam A2 achieved a higher ultimate load-carrying capacity than beam A3. Beam A2 and A3 was strengthened with the same FRP thickness of 1mm, and in comparison, beam A2 which were strengthened with 4mm concrete to FRP interface thickness (4mm Epoxy resin of Sikadur(R)-31 thickness) achieved a higher ultimate load-carrying capacity than beam A3 which was strengthened with 8mm concrete to FRP interface thickness (8mm Epoxy resin of Sikadur(R)-31 thickness). The increase in the load-carrying capacity for beam A2 is 7% relative to A3, Also beam A4 and A5 was strengthened with the same FRP thickness of 1.5mm, and in comparison, beam A5 which was strengthened with 8mm concrete to FRP interface thickness (8mm Epoxy resin of Sikadur(R)-31 thickness) attained a higher ultimate load-carrying capacity than beam A4 which was strengthened with 4mm concrete to FRP interface thickness (4mm Epoxy resin of Sikadur$^{(R)}$-31 thickness). The increase in the load-carrying capacity for beam A5 is 15% relative to A4. The study results also validate the comparison of beam A2 and beam A4, given that beam A2 and beam A4 was strengthened with the same 4mm concrete to FRP interface thickness (4mm Epoxy resin of Sikadur$^{(R)}$-31 thickness), beam A2 which was strengthened externally with a FRP thickness of 1mm had a higher ultimate load-carrying capacity than beam A4 which was strengthened externally with a FRP thickness of 1.5mm. The increase in the ultimate load for beam A2 is 1.3% compared to A4, whereas beam A5 is 9% higher than beam A3.

V. CONCLUSION

The contemporary study aimed to examine the effect of FRP-to-concrete interface thickness on the load-carrying capacity of reinforced concrete beams strengthened externally. The study was based on the comparison of interface thickness and load-bearing capacity. From the discussed results, the following conclusions were reached:

I. Beams strengthened externally with FRP sheets performed better than beam without external reinforcement
II. For beams strengthened externally with an FRP sheet of 1mm thickness, the concrete to FRP thickness (adhesive thickness) of 4mm obtained a favorable result.
III. For beams strengthened externally with an FRP sheet of 1.5mm thickness, the concrete to FRP thickness (adhesive thickness) of 8mm obtained a favorable result.
IV. Beams with an externally reinforced FRP transferred the performance of the beam from ductile behavior to brittle failure.

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