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Effect of GFRP Anchor on the Performance of Reinforced Concrete Beams to Mitigate The Debonding Failure

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Abstract: Strengthening reinforced concrete (RC) beams using fiber-reinforced polymer (FRP) materials has become a widely accepted technique in structural engineering due to its efficiency, light weight, and resistance to corrosion. Among these materials, glass fiber-reinforced polymers (GFRP) are commonly used for flexural strengthening by bonding fabric sheets to the tension side of beams using epoxy adhesives. In this study, an experimental program was carried out to investigate the flexural behavior of an RC beam strengthened with a GFRP fabric sheet bonded to its bottom surface using epoxy. Standard three-point bending was applied to the beam. During loading, premature debonding between the GFRP sheet and the concrete surface was observed at advanced stages, leading to slip and reduction in strengthening efficiency. To mitigate this issue, GFRP anchors, made from the same material as the strengthening sheet were introduced to improve the bond. These anchors had varying dimensions in width and height to assess their influence on the overall performance of the beam. The results revealed that both the load-carrying capacity and displacement capacity of the beam increased significantly with the addition of the anchors. The highest level of performance enhancement was achieved when the anchor width was maximized and the height remained lower than the width, suggesting that wider and flatter anchors enhance bond performance more effectively. A clear proportional relationship was found between anchor width and the beam's structural performance, while increased anchor height showed a diminishing effect. These findings highlight the critical role of anchor geometry in optimizing the performance of GFRP-strengthened RC beams.

GFRP Ankraj Boyutlarının GFRP Levhalar ile Güçlendirilmiş Betonarme Kirişlerin Performansına Etkisi

Anahtar Kelimeler
GFRP ankraj, FRP uç sıyrılması, Güçlendirme, FRP

Öz: Fiber takviyeli polimer (FRP) malzemeler kullanılarak betonarme kirişlerin güçlendirilmesi, verimliliği, hafifliği ve korozyona karşı direnci nedeniyle yapı mühendisliğinde yaygın olarak kabul edilen bir teknik haline gelmiştir. Bu malzemeler arasında, cam elyaf takviyeli polimerler (GFRP), epoksi yapıştırıcılar kullanılarak kirişlerin eğilme güçlendirmesinde yaygın olarak kullanılmaktadır. Bu çalışmada, epoksi kullanılarak alt yüzeyinden GFRP levha ile güçlendirilmiş bir betonarme kirişin eğilme davranışını incelemek için deneysel bir program gerçekleştirilmiştir. Betonarme kirişler, standart bir eğilme yükleme senaryosunu simüle etmek için basit mesnetli ve tek nokta yükü altında test edilmiştir. Deneysel çalışmalarda yükleme sırasında, GFRP levha ile beton yüzey arasında erken ayrılma bilinen bir sorundur ve bu sorun güçlendirme verimliliğinde azalmaya yol açmaktadır. Bu çalışmada erken kopma sorununu gidermek için GFRP levhaların uç noktalarına farklı genişlik ve yükseklikte GFRP kumaşlardan ankrajlar uygulanmıştır. Sonuçlar hem kirişin yük taşıma kapasitesinin hem de yer değiştirme kapasitesinin ankrajların etkisiyle önemli ölçüde arttığını ortaya koymuştur. En etkili iyileştirme, ankraj genişliği maksimuma çıkarıldığında ve yüksekliği ise orta seviyelerde iken meydana gelmiştir. Ankraj genişliği ile kirişin yapısal performansı arasında net bir ilişki bulunurken, artan ankraj yüksekliğinin azaltıcı bir etki gösterdiği görülmüştür. Bu bulgular, ankraj geometrisinin GFRP ile güçlendirilmiş betonarme kirişlerin performansını optimize etmedeki kritik rolünü olduğunu ortaya koymuştur.

1. INTRODUCTION

With the rapid advancement of technology and construction practices, conventional strengthening techniques such as concrete jacketing and steel plate reinforcement are gradually losing favor among construction professionals. These traditional methods often present practical and economic challenges, including complex installation procedures, increased labor demand, and long-term maintenance concerns. In recent years, fiber reinforced polymers (FRPs) have emerged as a promising alternative for the strengthening and rehabilitation of both concrete and steel structures. These composite materials offer a combination of desirable properties, including exceptionally high tensile strength, resistance to corrosion, and lightweight, which contribute to reduced installation time and lower lifecycle costs compared to conventional solutions. As a result, the use of FRP materials in structural retrofitting has gained significant attention for providing efficient, durable, and cost-effective reinforcement strategies [1–9]. Numerous experimental and analytical studies have confirmed that externally bonding fiber-reinforced polymer (FRP) systems to reinforced concrete (RC) elements is an effective method to significantly enhance their flexural strength and load-carrying capacity [10–12]. However, despite these advantages, this strengthening technique still encounters some limitations, especially under failure conditions. Several investigations have revealed the emergence of novel failure mechanisms that may adversely impact the overall performance of FRP systems when applied in structural rehabilitation [13].

According to [10], typical failure modes observed in RC beams strengthened in flexure with externally bonded FRP plates include the following: a) FRP rupture; b) Compressive concrete crushing; c) Shear failure; d) Concrete cover separation (CCS); e) Plate-end interfacial debonding; f) Intermediate flexural crack (IC)-induced debonding; g) Intermediate flexural-shear crack (IC)-induced debonding. Among all debonding-related failure types, IC-induced debonding and concrete cover separation (CCS) near the plate ends have been reported as the most frequently observed and critical failure modes. These are illustrated in Figure 1 as follows: (a) ideal bond between FRP and RC beam, (b) interfacial debonding due to flexural cracking, (c) interfacial debonding due to flexural-shear cracking, and (d) concrete cover separation [14–15]. Several parameters influence the likelihood and type of debonding failure, including the thickness of the concrete cover, number and diameter of tensile steel bars, the distance between the FRP plate end and the beam support, and FRP properties such as length, width, thickness, and modulus of elasticity. Additional contributing factors include the shear span-to-depth ratio, the interaction between shear and bending moments, cross-sectional geometry, and compressive strength of the concrete [14–18].

One of the most concerning forms of failure is plate-end (PE) debonding, which is particularly brittle and tends to occur before the tensile reinforcement yields. This premature failure leads to underutilization of the FRP's tensile strength, making it essential to provide a suitable anchorage at the plate ends to ensure a more ductile response and maximize the effectiveness of externally bonded FRP strengthening systems [14].

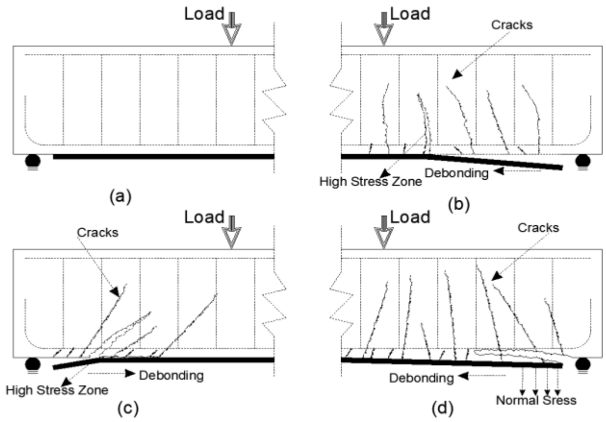

Figure 1. Typical failure modes observed in RC beams strengthened in flexure with externally bonded FRP plates

To mitigate the risk of such brittle debonding failures, several anchorage techniques have been proposed in the literature [14,16,19]. Among these, the use of U-Wrap anchors applied along the beam's sides has gained prominence due to its practicality, quick installation, ease of execution without the need for pre-drilling, and superior resistance to corrosion—an essential factor for long-term durability [14,20].

Consequently, various design standards have begun to incorporate detailed recommendations and guidelines concerning the use of externally bonded FRP for concrete strengthening, specifically aimed at minimizing debonding risks and ensuring system reliability [20–24]. Nevertheless, while several studies have explored the effectiveness of U-Wrap anchors in reducing or eliminating debonding failures [16,20,25,26], there remains a lack of focused research addressing specific design optimization aspects. Furthermore, most existing studies do not comprehensively quantify the enhancement achieved through these anchorage systems, do not determine the effect of changing the anchor dimensions, and reliable design formulas for predicting their contribution are still lacking [7,9,13,14,16,17,19,25– 33].

A recent analytical study using Abacus software examined the effect of anchor geometry on bending behavior and demonstrated that increasing anchor width is more effective in increasing load capacity than increasing anchor height [34]. This experimental study aims to investigate the influence of anchor geometry on the flexural performance of reinforced concrete beams strengthened with a single layer of unidirectional glass fiber-reinforced polymer (GFRP) sheets applied to the tension face. A total of six beams were tested under four point loading: two reference beams, one unstrengthened and one strengthened with GFRP only to assess the baseline effect of external reinforcement, and four beams strengthened with GFRP sheets and end anchors of varying dimensions to evaluate the impact of anchor width and height on structural behavior.

2. EXPERIMENTAL STUDY

A series of flexural tests were conducted on six reinforced concrete beams, all cast and prepared under the same conditions. Each beam had a concrete compressive strength of 10 MPa, and identical reinforcement detailing: two 12 mm diameter steel bars in both the top and bottom longitudinal layers, and 8 mm diameter stirrups spaced at 75 mm intervals, serving as transverse reinforcement. The cross-sectional dimensions of each beam were 150 mm in width and 250 mm in height, with a concrete cover of 25 mm to the reinforcement. Each beam was designated with a specific name corresponding to the type and configuration of the applied strengthening system as follows:

- Control Beam: CB
- Control Beam strengthened with single layer GFRP on the bottom face: L1C
- Beam with 10cm width and 10cm height, GFRP end anchor and single layer GFRP strengthened: L1W10H10
- Beam with 10cm width and 25cm height, GFRP end anchor and single layer GFRP strengthened: L1W10H25
- Beam with 20cm width and 25cm height, GFRP end anchor and single layer GFRP strengthened: L1W20H25
- Beam with 25cm width and 10cm height, GFRP end anchor and single layer GFRP strengthened: L1W25H10

In this study, the experimental design matrix was developed based on a combination of previous finite element analyses, available literature, and practical considerations. The selected anchor dimensions (i.e., 10×10, 10×25, 20×25, 25×10 cm) allowed for isolating the influence of anchor width and height on the flexural behavior of RC beams strengthened with GFRP. These dimensions were chosen to examine the effect of increasing anchor width while keeping height constant, and vice versa, ensuring a controlled parametric evaluation. This methodology ensures the findings are applicable to practical strengthening scenarios. Table 1 shows the variables of experimental study.

Tablo 1. Parametric study matrix

Sample name	Strirrup spacing (mm)	Upper reinforcement	Bottom reinforcement	FRP type	Epoxy Layer	Achor height (mm)	Anchor width (mm)
B	Ø8/75			GFRP	NA	NA	NA
L1C	Ø8/75			GFRP		NA	NA
L1W10H10	Ø8/75	2T12	2T12	GFRP	One Layer Bottom	100	100
L1W10H25	Ø8/75			GFRP		250	100
L1W20H25	Ø8/75			GFRP		250	200
L1W25H10	Ø8/75			GFRP		100	250

Dimensions and schematic views of the designed beams are shown in Figure 2.

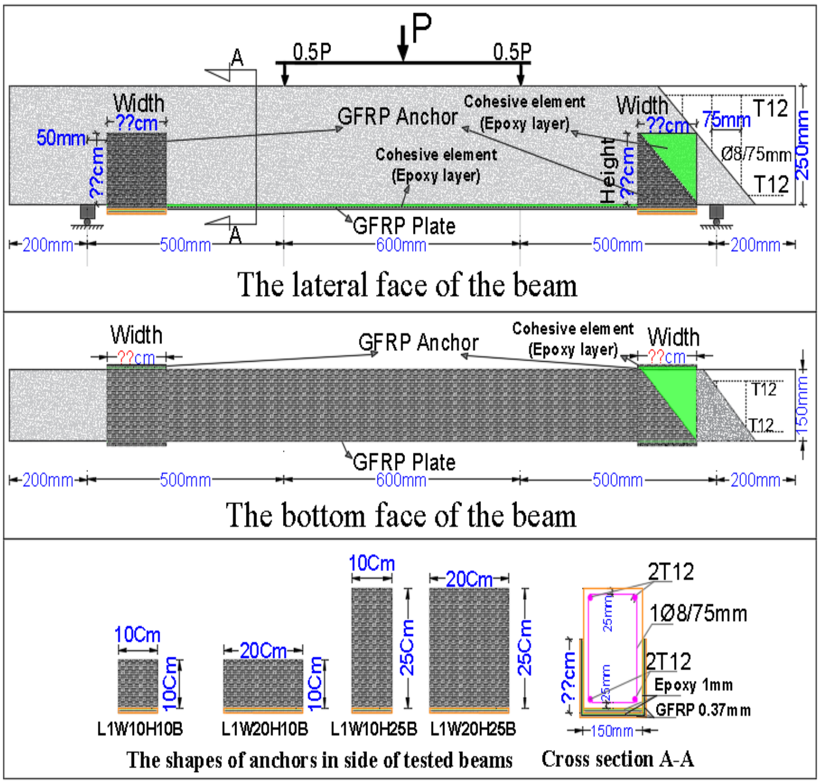

Figure 2. Schematic diagram of anchor placement and dimension changes

2.1. Properties of Materials

2.1.1. Concrete density test

The density of the concrete used in this study was determined by measuring the mass and volume of standard cylindrical specimens in accordance with relevant testing procedures (e.g., ASTM C642). A cylindrical sample with dimensions of 150 mm in diameter and 300 mm in height was used for this purpose (Figure 3).

The average mass of the specimen was recorded as 12.5 kg, and based on its geometric volume (calculated as $\pi \times r^2 \times h$), the resulting unit weight (density) of the concrete was computed to be approximately 23.59 kN/m³. This value is within the typical range for normal-weight concrete, indicating that the mix design used provides a good balance between strength and density, suitable for structural applications.

Figure 3. Concrete density test

The measured density also confirms the homogeneity and proper compaction of the concrete mix, which is essential for the effective bonding with both internal reinforcement and externally bonded GFRP sheets used in the strengthening system.

2.1.2. Slump test

To evaluate the workability of the concrete mix used in this study, a slump test was conducted according to standard procedures (ASTM C143/C143M). The test aimed to assess the consistency and fluidity of the fresh concrete before casting the beam specimens. The measured slump value was 12 cm, indicating a concrete mix with medium to high workability (Figure 4).

Figure 4. Slump test of cast in place concrete

This level of slump is considered appropriate for structural elements such as reinforced concrete beams, as it facilitates adequate compaction and bonding with embedded reinforcement without leading to segregation or excessive bleeding. The achieved slump value also ensured proper surface contact with the bonded GFRP sheet and minimized the presence of voids at the interface, which is critical for the effectiveness of the strengthening system.

2.1.3. Compressive strength test

To evaluate the compressive strength of the concrete used in this study, standard compression tests were conducted on both cylindrical and cubical specimens in accordance with ASTM standards (Figure 5). Concrete cylinders measuring 150 mm in diameter and 300 mm in height (15×30 cm) were cast and tested after 28 days of curing, yielding an average characteristic compressive strength of 10 MPa. In parallel, cubical specimens measuring 200 mm on each side (20×20×20 cm) were tested under the same conditions and exhibited an average compressive strength of 13 MPa at 28 days.

Figure 5. Compressive strength test of concrete samples

The difference in strength values between the cylindrical and cubical specimens is consistent with expected conversion factors, as cube tests typically produce higher results due to differences in specimen geometry and stress distribution during testing. These strength levels indicate that the concrete used was of low to moderate strength, which aligns with the purpose of the experimental program aiming to investigate the performance of externally strengthened RC beams under realistic conditions.

These values serve as a reference for analyzing the flexural behavior and failure mechanisms observed in the beam tests, and for assessing the effectiveness of the GFRP strengthening system under practical material limitations.

2.1.4. Tensile strength of steel reinforcement

To determine the mechanical properties of the steel reinforcement used in the concrete beams, tensile tests were conducted on steel bars of two different diameters: 8 mm and 12 mm, following standard testing procedures

ASTM A370 (Figure 6). The results provided essential data regarding the yield and ultimate strengths of the reinforcement, which are critical for evaluating the flexural performance of the strengthened beams.

For the 8 mm diameter bars, the average yield stress was measured at 365 MPa, while the ultimate tensile strength reached 525 MPa. In contrast, the 12 mm diameter bars showed a higher average yield stress of 425 MPa and an ultimate tensile strength of 585 MPa.

Figure 6. Tensile strength test of steel reinforcement

The variation in strength between bar diameters reflects the manufacturing and mechanical differences associated with size, and provides a reliable basis for the flexural design and analysis of the tested RC beams. These steel properties were taken into account when interpreting the results of the beam tests and assessing the contribution of both internal steel reinforcement and external GFRP strengthening.

2.1.5. Tensile test of CFRP fabric sheets

To determine the tensile properties of the externally bonded GFRP fabric sheets used for strengthening, a series of uniaxial tensile tests were carried out (Figure 9). The GFRP fabric had a nominal areal weight of 330 gr/m².

Figure 7. One-way oriented polymer reinforced fiberglass textile plates

Test specimens were prepared with average dimensions of 17.5 cm in length, 4 cm in width, and a thickness of 0.37 mm (Figure 7).

Figure 8. Tensile tested of GFRP samples

To ensure uniform stress distribution and prevent localized failure at the gripping points, two metal plates were adhesively bonded to both ends of each specimen using Sikadur-330 epoxy resin, forming effective end-tabs for load transfer during testing as shown in Figure 8. The specimens were then loaded using a universal testing machine until failure.

The results showed an average tensile strength of 300 MPa, with an elongation of approximately 3 mm prior to rupture. These values confirm the high tensile capacity of the GFRP fabric, making it suitable for flexural strengthening of reinforced concrete elements. The bonding technique with epoxy and metal end-tabs proved effective in reducing stress concentrations and allowing for accurate measurement of tensile behavior.

Figure 9. Tensile test of GFRP samples

The obtained tensile characteristics were essential in evaluating the contribution of the GFRP sheets to the overall performance of the strengthened beams, particularly in terms of load redistribution and crack control under flexural loading.

2.1.6. Epoxy adhesive properties

The bonding between the GFRP fabric sheets and the bottom surface of the reinforced concrete beam was achieved using Sikadur-330, a high-performance two-component thixotropic epoxy-based adhesive, specifically formulated for structural bonding applications in FRP strengthening systems (Figure 10). This adhesive is widely used due to its excellent mechanical and physical properties, including strong adhesion, ease of application, and compatibility with both concrete and FRP surfaces. The key mechanical and physical properties of Sikadur-330, as provided by the manufacturer, are summarized in Table 2.

Table 2. The properties of Sikadur-330 [34]

Tensile Strength	Compressive Strength	Flexural Strength	Shear Strength
~30 MPa	~70 MPa	~45 MPa	~18 MPa
Young's Modulus (Tensile)		Elongation at Break	Density
~4500 MPa		~0.9 %	~1.31 kg/L

Application Temperature: +10°C to +35°C
Curing Time: Initial cure in 12 hours; full cure in 7 days

Figure 10. Sikadur-330

These properties ensured efficient stress transfer between the GFRP and concrete, playing a crucial role in the effectiveness and durability of the strengthening system used in this experimental study.

2.2. Experimental Procedure

Five beams were externally strengthened on the bottom tension face using Single layer of textile glass fiber reinforced polymer (GFRP) sheets, which were bonded to the concrete surface using Sikadur-330 epoxy adhesive. To enhance the bond performance and delay premature debonding, GFRP anchors of varying geometries were installed on selected beams, and the flexural behavior was evaluated using a three-point bending test setup, as shown in Figure 11.

Figure 11. Examples of RC retrofitted beams with GFRP plates and anchors

This setup enabled a comparative analysis of load capacity and displacement behavior across all beam specimens, particularly focusing on the role of anchor geometry in enhancing the efficiency of GFRP-strengthened concrete members.

3. CONCLUSIONS AND DISCUSSION

3.1. Load–Deflection Response From Three-Point Bending Tests Of GFRP-Strengthened Beams With Side Anchors

A series of three-point bending tests as Figure 12 in were conducted to examine the flexural behavior of reinforced concrete RC beams strengthened with externally bonded glass fiber reinforced polymer (GFRP) plates.

To address premature debonding of the GFRP plates, mechanical anchors were applied along the sides of the beam webs. The anchors were fabricated in various dimensions, with variations in both height and width, to assess their influence on the load capacity and deflection characteristics of the strengthened beams.

Figure 12. The machine of applied load on the tested beams

Figure 13. Appearance of C collapsed sample after three-point bending test

RC Beams equipped with GFRP anchors exhibited higher peak loads and greater deflection capacities, confirming the contribution of optimized anchorage to delaying or preventing debonding failures, which can be noticed in Figures from 13 even 18.

Figure 14. Appearance of L1C collapsed sample after three-point bending test

Figure 15. Appearance of L1W10H10 collapsed sample after three-point bending test

Figure 16. Appearance of L1W10H25 collapsed sample after three-point bending test

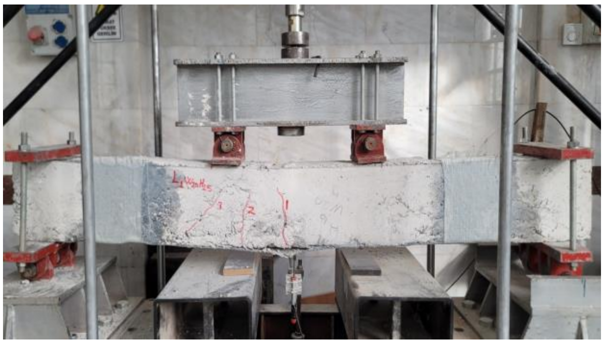

Figure 17. Appearance of L1W20H25 collapsed sample after three-point bending test

The experimental results are illustrated in the load–deflection curves shown in Figure 19. Furthermore, the beams were loaded until collapse occurred due to flexural cracks as a result of debonding failure. These curves reflect the effectiveness of the side anchors in enhancing flexural performance and demonstrate the role of anchor geometry in improving load resistance and ductility.

Figure 18. Appearance of L1W25H10 collapsed sample after three-point bending test

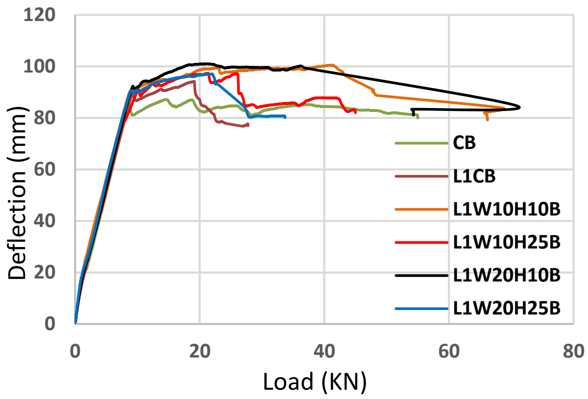

Figure 19. Diagram of three-point bending tests of GFRP-strengthened beams with side anchors and control beam

It is noted that the addition of the anchor led to an increase in the load capacity and ductility of RC beams retrofitted with GFRP plate.

3.2. The Max Capacity Load Of RRC Beams With GFRP Plate

To know the amount of improvement of the load capacity and the effectiveness of the U-Wrap anchor in reducing the problem of debonding failure, the ultimate moment that the beam can be loaded was calculated by information in Table 3, Eq (1), and Eq (2) which is illustrated in Figure 20, according to the ACI 440.2R [35] and in Figure 21, according to the Canadian code ISIS [36] considers a linear strain variation over the depth of sections, and uses the value of 0.003 for the maximum concrete compressive strain. Then the ultimate force was calculated after reducing the arm (500 mm) shown according to the Figure 10 and that is for RRC beam with GFRP plate.

$$M_u = \varphi_s A_s \sigma_s \left(d - \frac{\beta c}{2}\right) + \varphi_{frp} A_f \sigma_f \left(d_f - \frac{\beta c}{2}\right) + \varphi_s A'_s \sigma'_s \left(\frac{\beta c}{2} - d'\right) \qquad (1)$$

$$M_u = \text{Ø}Mn = \text{Ø}\left[A_s \sigma_s \left(d - \frac{\beta_1 c}{2}\right) + \varphi_{frp} A_f \sigma_{fe} \left(h - \frac{\beta_1 c}{2}\right) + A'_s \sigma'_s \left(\frac{\beta_1 c}{2} - d'\right)\right] \qquad (2)$$

Mu: Ultimate moment, Nmm, Mn: Nominal moment, Nmm. α, β: Stress-block factors for concrete, Ø: The reduction factors, c: Depth of neutral axis, mm. As, Af and A's are the areas of the tensile reinforcing bars, GFRP sheets and compressive reinforcing bars, respectively, mm^2. φ: The reduction factors' of 0.6, 0.85 and 0.75 for concrete, steel and FRP plate, respectively. σs, σ's, σf Tensile, compressive strength of steel and tensile strength of GFRP Plate, respectively.

According to the use of the previous equations, the load capacity for Eq (1) is 84.3 kN and the load capacity for Eq (2) is 100 kN.

Table 3. Mechanical properties of used materials

Steel	Elastic modulus	Es	210E+3	MPa
	Yielding stress	fy	425	MPa
	Poisson ratio	ν	0.3	-
Concrete	Compression stress	f'c	10	MPa
GFRP	Elastic modulus	E_{GFRP}	65E+3	MPa
	Yielding stress	f_{CFRP}	300	MPa

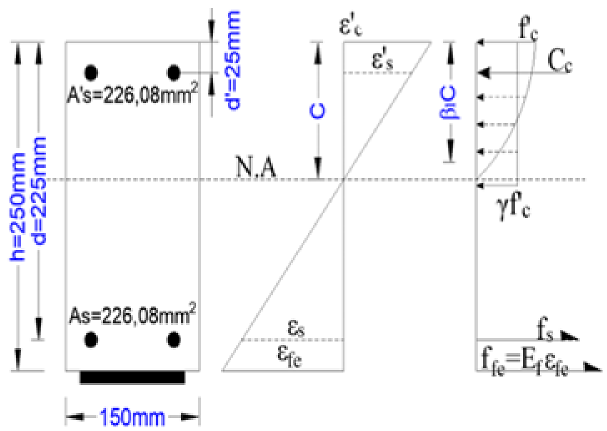

Figure 20. Ultimate moment according to ACI 440.2R [34]

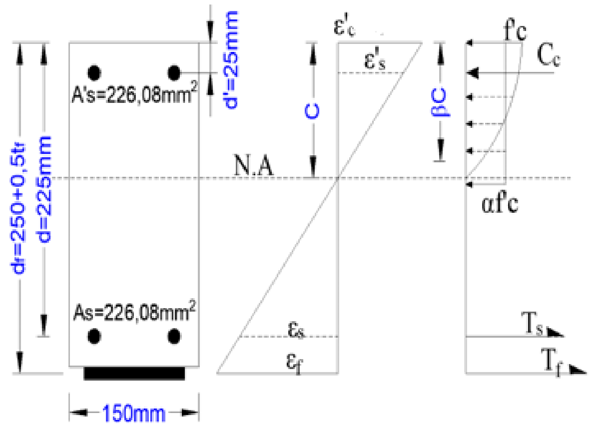

Figure 21. Ultimate moment according to ISIS [35]

3.3. The Improvement Of Capacity Load Of RRC Beams With GFRP Plate And Anchorage:

To observe the amount of improvement in the load capacity, the values of the maximum load carried by each beam during experiment and its corresponding deflection are listed in Table 4.

The obtained results generally align with previous research findings that emphasized the beneficial role of anchors in enhancing bond performance and flexural strength of RC beams (14, 25, 27, 30, 31). However, unlike some prior studies that suggested anchor height plays a significant role, our results showed diminishing improvement with increasing height. This divergence may be attributed to stress concentration patterns and the bond behavior at the tension face. Furthermore, differences in concrete strength and anchorage installation techniques across studies may account for discrepancies. This highlights the necessity of optimizing anchor geometry specifically for each application scenario.

Table 4. Maximum load-deflection values for the tested beams

Tested sample	Max load (P_{kN})	Deflection (Δ_{mm})
C	87.15	14.51
L1C	94.20	19.12
L1W10H10	100.51	40.97
L1W10H25	97.35	21.24
L1W20H25	97.08	21.98
L1W25H10	101.06	20.99

The previous values are also represented graphically in Figure 22.

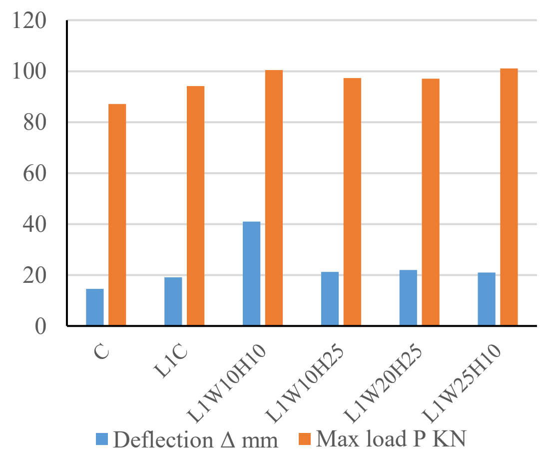

Figure 22. Chart of maximum load values and corresponding deflection for the tested beams

It is clear that increasing the height of the anchor gives a lower load capacity, while increasing the width of the anchor increases the load capacity. The effect that each anchor adds to prevent the sliding of the GFRP plate retrofitting to RC beam is studied as a percentage of the maximum load value provided only by the GFRP plate retrofitting to RC beam, and this is shown in Figure 23.

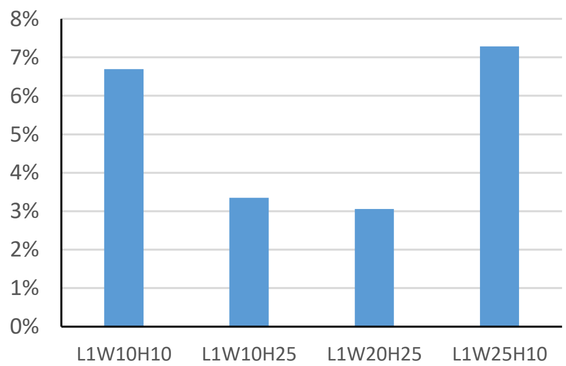

Figure 23. The relative increase in the load capacity after adding different dimensional models of GFRP anchors

Figure 23 shows that adding an anchor improves the load capacity, with the best result being an anchor width of 25 cm and a height of 10 cm, resulting in a 7.28% increase in load capacity.

Table 5. Relative comparison between the load capacity from the code and the experiment

Code	P_{kN}	Comparing with L1C	Comparing with L1W25H10
ACI 440.2R	84.3	-10.5%	19.9%
ISIS	100	6.2%	1.1%

Comparing the theoretical load capacity values from the codes with the laboratory values, it can be noted that when the GFRP plate was added to the beam (L1C), the theoretical load capacity values were 10.5% lower in the American code (ACI 440.2R), in contrast to the Canadian code (ISIS), which gave results 6.2% higher than the laboratory values. Comparing the code values with the maximum values for the L1W25H10 anchor, we find that adding the anchor produced load capacity results that were 19.9% higher than the code results for the American code and 1.1% higher than the Canadian code. This means that adding the anchors mitigated the slippage problem between the GFRP plate and the tensioned RC beam surface, bringing it closer to the theoretical values provided by the code's theoretical calculations.

4. CONCLUSION

This experimental study investigated the flexural performance of RC beams strengthened with externally bonded GFRP sheets and equipped with U-wrap GFRP anchors of varying dimensions. The results confirm that anchorage systems significantly enhance the structural performance of GFRP-strengthened beams by mitigating premature debonding failure and increasing both load capacity and ductility.

Key findings from this research are summarized as follows:

- Effectiveness of GFRP Strengthening:
  The use of externally bonded GFRP sheets alone improved the flexural capacity of RC beams compared to the unstrengthened control beam, demonstrating the fundamental benefit of composite reinforcement.
- Critical Role of Anchors:
  Beams retrofitted with both GFRP sheets and U-wrap anchors showed a significant increase in ultimate load capacity compared to beams strengthened with GFRP sheets alone. This indicates that proper anchorage can significantly delay the onset of debonding and allows better utilization of the GFRP's tensile strength.
- Influence of Anchor Geometry:
  The width of the U-wrap anchor had a more pronounced effect on load capacity enhancement than the anchor height. Wider anchors led to higher peak loads and improved flexural performance, whereas increasing anchor height showed diminishing or negative returns.
- Load-Deflection Behavior:
  Anchored beams displayed greater ductility and higher deflection at peak load compared to non-anchored specimens. This implies improved energy absorption and structural resilience under loading.
- Theoretical Validation:
  The experimental results were found to be in reasonable agreement with predictions made using ACI 440.2R and the Canadian ISIS code, supporting the validity of current design models and the relevance of accounting for anchorage effects in flexural capacity calculations.
- Design Implications:
  The study highlights the necessity of optimizing anchor dimensions for maximizing the benefits of FRP retrofitting systems. In particular, anchor width should be considered a key parameter in design guidelines aimed at enhancing the effectiveness of FRP strengthening.

This study contributes to the ongoing development of efficient, durable, and cost-effective strengthening methods for RC structures. Future research should explore long-term durability, fatigue behavior, and the performance of hybrid anchorage systems under dynamic or seismic loading conditions.

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