CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 4, ISSUE 2, 2024, 176 – 185
DOI: https://doi.org/10.15282/construction.v4i2.10760

REVIEW ARTICLE

Shear Strengthening of RC Corbels with Carbon Fiber Reinforced Polymer Sheets: A Critical Review

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ABSTRACT - Reinforced concrete corbels are essential components in construction that function as short cantilevers to provide support for different pre-cast and pre-stressed structural elements. The corbels often experience failure modes such as shear, flexural, diagonal shear, anchoring loss, vertical splitting, and bearing failures. These modes arise due to variables such as insufficient reinforcing and inadequate detailing. In order to address these problems, the use of CFRP as a form of reinforcement may be used. This study aims to provide several methods for reinforcing corbels using CFRP jacketing, which is chosen for its exceptional strength-to-weight ratio and simplicity of application. The efficacy of CFRP reinforcements is evaluated by means of load capacity, load-displacement curves, and fracture patterns. The addition of two layers of external CFRP reinforcement on concrete corbels resulted in an average increase in load bearing capacity of up to 35%. Furthermore, the experimental results have shown that CFRP has the capability to substantially enhance the load-bearing capacity of RC corbels, even if it does not reach the levels of the original design.

ARTICLE HISTORY
Received : 24th May 2024
Revised : 20th June 2024
Accepted : 09th July 2024
Published : 27th Aug. 2024

KEYWORDS
Carbon fiber reinforced polymer,
Mode of failures,
Reinforced concrete corbels,
Shear resistance

1. INTRODUCTION

1.1 Background

Corbels are known as short cantilevers that mainly perform as deep beams or simple trusses. They are commonly used to support Pre-cast structural elements, such as pre-cast beams and pre-stressed beams, can be supported by corbels or brackets. Corbels, which are typically cast with the column or wall members, have become a standard feature in the construction of buildings. their primarily role is to withstand the ultimate sheer force of the beam as well as the ultimate horizontal action resulting from beam shrinking [1-3]. Corbels are primarily designed to provide the vertical reaction and sometimes consideration for horizontal frictional forces. Corbels reinforcement is primary tension steel and horizontal bars. Also, the horizontal reinforcement bars are used to resist shear force and the top longitudinal bars used to resist flexure as shown in Figure 1[4].

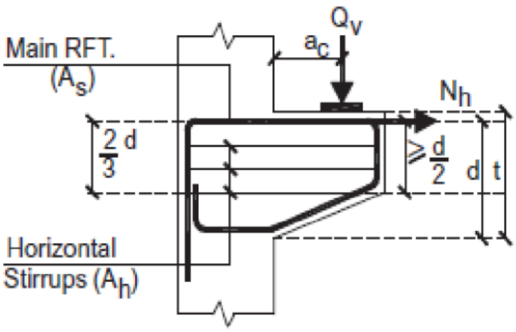

Figure 1. Corbels reinforcement details [4]

Shakir, Q.M [5] reported that a corbel might fail by several crushing of the horizontal and diagonal concrete strut, crushing of the compression zone, and yielding of principal tensile reinforcement. The different modes of failure are shown in Figure 2. Figure 2. (a) demonstrates the flexural or bending failure and this may happen due to small amount of main steel reinforcement or the ratio of a/d bigger than 1. Figure 2 (b) illustrates the Diagonal shear failure which is starts under the concentrated load application and toward the bottom of corner junction of the corbel to the column face. Figure 2 (c) shows the Shear failure which is beginning at the upper corner of the corbel and towards the lower fibers. The failure is almost vertically throw the brackets due to insufficient amount of stirrups and the ratio of a/d is significantly less than 1. Figure 2 (d) represent the loss of anchorage due to the lack of detailing of the embedded length. Figure 2 (e) shows the vertical splitting failure by the direct tension due to applied high horizontal load and small thickness of corbels. Figure 2 (f) illustrates the Bearing failure which occurs due to crushing the concrete under the load bearing when the bearing area

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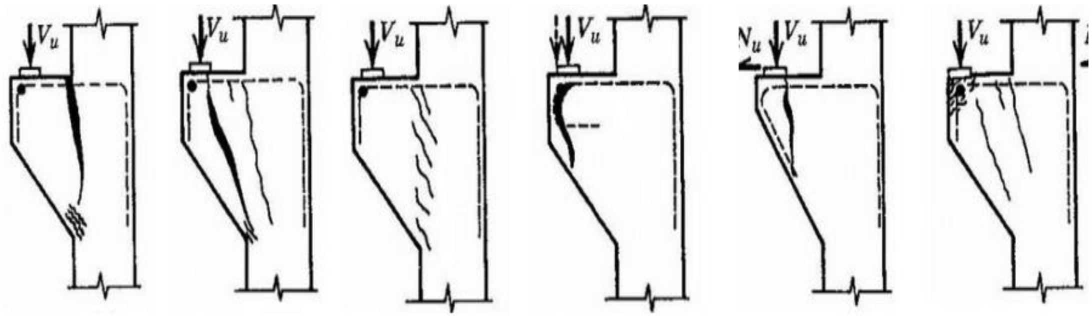
is not adequately proportioned or lack in the seat plate detailing. One of the most effective ways to strengthening corbels is CFRP wrapping bye different layers and orientation. This study reviews CFRP active strengthening of normal strength reinforced corbels and effect on shear strength and behavior. Thus, several researches have been reviewed and evaluating their results within critical discussion.



(a) (b) (c) (d) (e) (f)

Figure 2. Different types of failure in reinforced concrete corbels [5]

1.1.1 Reinforced concrete corbels

Reinforced concrete corbels are structural elements used to transfer loads from a column, wall, or beam to another supporting structure, typically another beam or column. The characterization of corbels includes the geometry and the shear span to depth ratio. They usually have a low shear span to depth ratio, which means they are relatively deep in comparison to their horizontal projection. The designs of corbels methods are the strut-and-tie model in many cases, which simplifies complex stress patterns into a truss-like model. Appropriate design according to ACI 318 or BS 1997 helps prevent failure by avoiding certain problematic bearing pad positions [6].

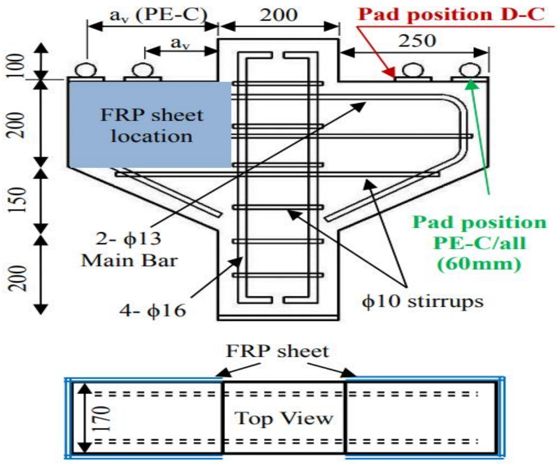


Figure 3. Corbels design details [6]

Figure 3 present the typical reinforcement and the location of bearing pad. Although, one of the most important factors is placement of the bearing pad which can lead to local failures, especially if the pad is extended beyond the straight portion of the main flexural bar or beyond the interior face of the transverse anchor bar. The corbels can be strengthening by external fiber-reinforced polymer wraps, such as carbon fiber reinforced polymer. These materials are advantageous due to their high strength-to-weight ratio and ease of application.

1.1.2 Carbon fiber reinforced polymer

A CFRP overlay involves a layer of carbon fiber fabric to a structure using a resin, typically an epoxy, to improve its strength and stiffness. The technique typically follows some steps includes surface Preparation, applying epoxy, placement of CFRP, curing and finishing. The surface of the concrete is prepared to ensure a good bond. This often involves cleaning the surface, removing loose particles, and sometimes roughening it to enhance adhesion. Also typically a two part epoxy resin is mixed according to the manufacturer's specifications and the epoxy is applied to the carbon fiber sheet and the prepared surface of the concrete. Next the carbon fiber sheet is laid onto the surface, ensuring there are no air pockets or wrinkles. The epoxy is allowed to cure, bonding the CFRP to the concrete surface. After the epoxy is fully cured, finishing touches can be applied, such as additional protective coatings or painting if required [7].

1.2 Carbon Fibre Reinforced Polymer (CFRP) Sheets

The use of CFRP sheets for strengthening concrete structures has proven to be a reliable and effective method. The most important properties of CFRP are that it significantly improves the performance of concrete structures, as well as the lifespan of the concrete members [8]. Two major components make up CFRP sheets used for strengthening RC corbels. First, carbon fibres are the main reinforcement material used due to their high tensile strength and stiffness. Secondly, an epoxy resin polymer matrix binds the fibres to provide the load transfer and ensure protection against environmental effects such as moisture and chemicals [9].

The properties of CFRP sheets make them suitable for concrete structure strengthening applications. The properties include a very high strength-to-weight ratio, which allows CFRP sheets to have significant tensile strength without adding any weight to the structure. Also, the high stiffness of CFRP sheets enhances rigidity and improves the structure's performance. Moreover, CFRP sheets are extremely resistant to corrosion. Their excellent fatigue resistance allows them to withstand repeated load cycles without significant damage, improving their long-term durability. Also, epoxy resins used in CFRP systems ensure that the sheets don't expand or contract much when heated or cooled. This makes the sheets good at transferring weight between them and concrete surfaces [10].

The positives of using CFRP sheets for strengthening RC corbels include significantly increasing the load-carrying capacity of the RC members, which makes them capable of supporting higher loads. Additionally, CFRP provides long-term strengthening with minimum maintenance, enhancing the durability and longevity of the strengthened structures. The flexibility and ease of application allow CFRP sheets to be used on various shapes and sizes of RC structures, including beams, columns, slabs, walls, and corbels. The quick installation process of CFRP systems reduces the time for strengthening, which is more useful for projects requiring fast completion [11]. Despite their advantages, there are some negatives to CFRP sheets. First, the initial cost of CFRP materials and the specialised labour required for installation can be high. Secondly, ensuring effective adhesion and bond strength requires proper surface preparation, which can be time-consuming and may involve deboning or delamination. Third, repairing the damaged CFRP sheets can be complex and costly, and while CFRP itself is not flammable, the epoxy resin used in these systems can de-bond at high temperatures, which may compromise the strengthening system in the presence of fire [12].

Various applications use CFRP sheets to strengthen concrete members. Common applications for CFRP sheets include flexural and shear strengthening. Wrapping the CFRP sheets around the member's tension face improves its flexural strength by allowing it to support heavier loads. For shear strengthening, It applies CFRP sheets to the RC corbels, which enhances their shear capacity and prevents diagonal cracking and failure. Wrapping corbels with CFRP sheets improves their stiffness. CFRP sheets are also effective at controlling and arresting cracks in concrete structures, thereby maintaining structural integrity. Furthermore, CFRP sheets make structures more resilient by providing high protection against impact loads and blasting [13, 14]. The installation of CFRP sheets involves several important steps to ensure effective strengthening. Initially, it must clean the concrete surface, dry it, and remove any loose concrete to ensure a smooth and effective bond with the surface. The next step involves applying a primer to strengthen the bond between the concrete and the epoxy resin. The prepared surface then receives a layer of epoxy resin. Finally, place the CFRP sheet onto the epoxy resin, ensuring bonding and alignment, and allow the system to cure to achieve full strength over a specified period [15–17].

2. LITERATURE REVIEW

2.1 The Effect of Shear Span to Depth Ratio (a/d) on the Load Carrying Capacity of RC Corbels

In the study by Chandra shows various reinforced concrete corbel specimens were tested with different strengthening techniques using Carbon Fiber Reinforced Polymer 0.25mm thickness (CFRP) sheets. The specimens were labeled with codes such as D-C for the control specimen at the center, PE-C for the specimen with a shifting bearing pad at the edge, L2-CF-PE-C for the specimen with two layers of CFRP up to the column-corbels interface, L1-FW-PE-C for the specimen with a single layer of full wrap CFRP, and L2-FW-PE-C for the specimen with two layers of full wrap CFRP. The shear span ranged from 125mm to 220mm, with corresponding shear span to depth ratio varying from 0.625 to 1.222. The compressive strength of the specimens ranged from 41.89 MPa to 46.77 MPa. The study aimed to evaluate the effectiveness of CFRP strengthening in enhancing the load carrying capacity of the corbels. Through load tests and displacement measurements, the study demonstrated significant improvements in the ultimate load capacity of the strengthened corbels compared to the control specimen, highlighting the potential of CFRP wraps in retrofitting and strengthening reinforced concrete corbels as shown in Figure 4.

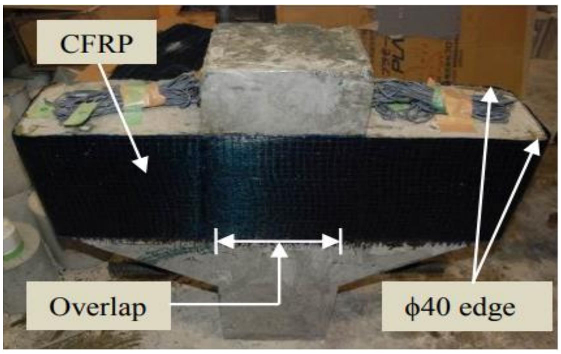


Figure 4. Strengthened corbel details [5]

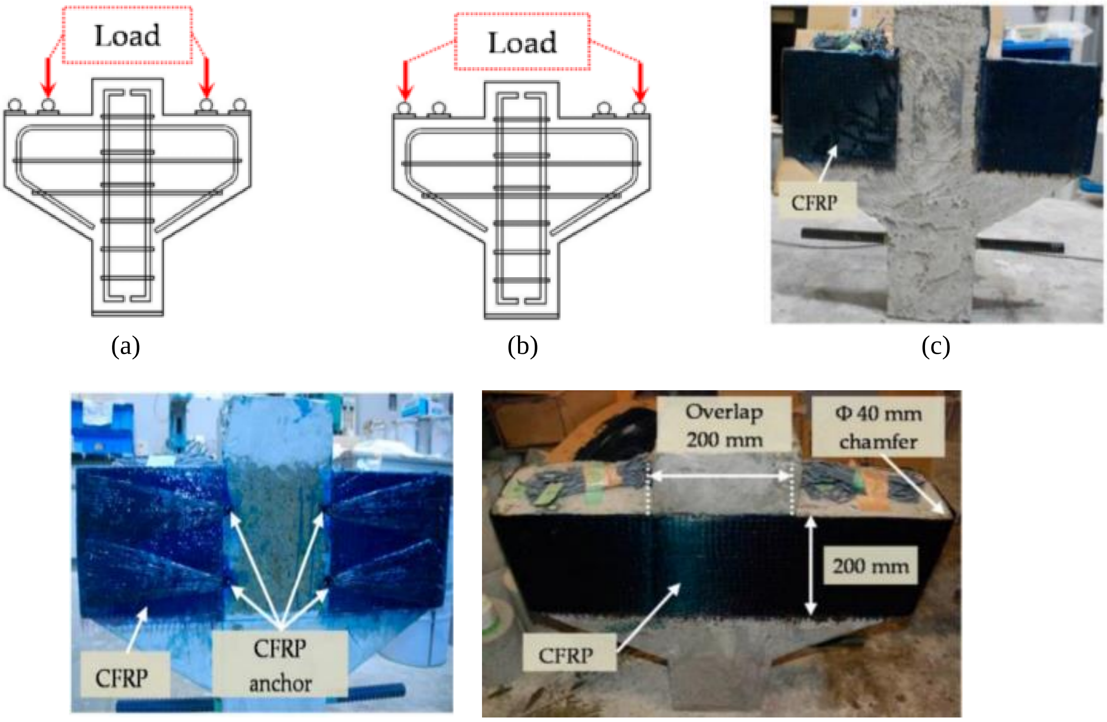


Figure 5. Strengthened corbels details (a) pad at the middle (b) pad at the edge (c) 2 layer CFRP wrap (d) 2 layer CFRP wrap (e) 1 layer CFRP full wrap with 200mm overlay [6]

Neupane et al. conducted different reinforced concrete corbel specimens were subjected to external wrapping with Carbon Fiber Reinforced Polymer (CFRP) sheets to investigate the impact on their load-carrying capacity. The specimens were categorized into different strengthening configurations, including D-C for the bearing pad at the middle (Figure 5 a), PE-C for the bearing pad at the edge(Figure 5 b), and CFRP-CF-2L for the specimen with a two-layer CFRP wrap terminated at the column face(Figure 5 c) and 2 layer CFRP wrap terminated at the column face with fiber anchor (Figure 5 d), 1 layer CFRP full wrap with 200mm overlay (Figure 5 d). The shear span varied from 125mm to 220mm, with shear span to depth ratio ranging from 0.694 to 1.222. The compressive strength of the specimens was in the range of 45.52 MPa to 46.77 MPa. The ultimate tensile strength for CFRP is 3.4 GPa and the modules of elasticity is about 245 GPa with the thickness of 25mm of CFRP. The study aimed to compare numerical and experimental results of load-displacement relationships to assess the effectiveness of CFRP strengthening. The results indicated a significant increase in the ultimate load-carrying capacity of the corbels when externally wrapped with CFRP, showcasing the potential of this strengthening method in improving the structural performance of reinforced concrete corbels.

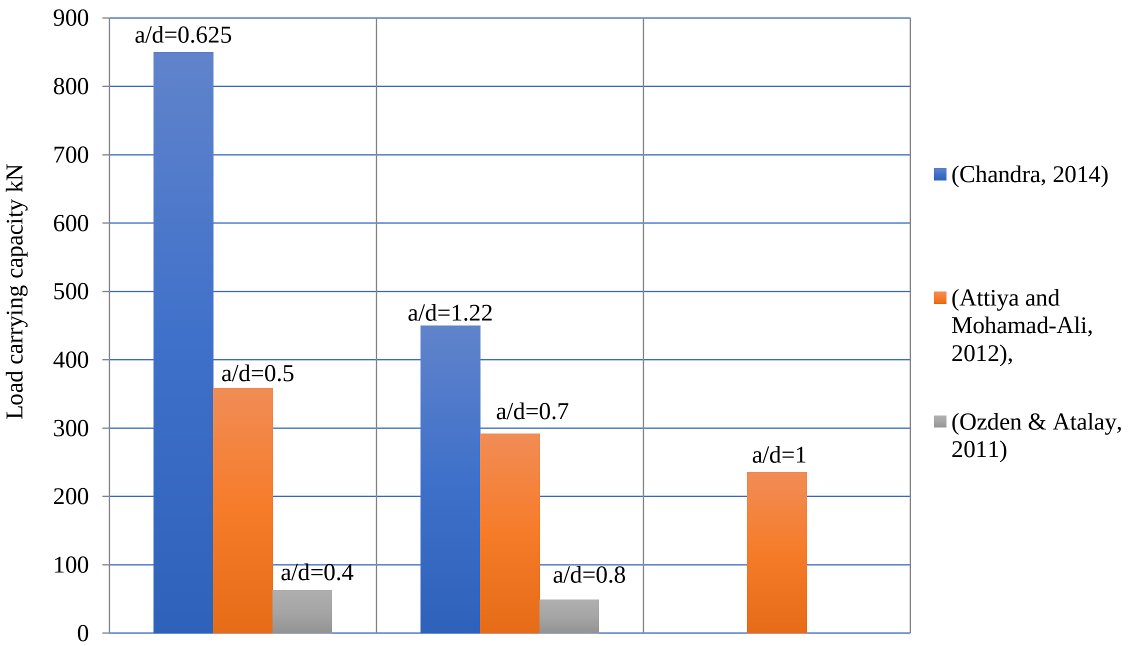


Figure 6. Load carrying capacity of corbels with different shear span to depth ratio

Figure 6 depicts the outcomes of various studies examining the use of CFRP for reinforcing RC corbels, focusing on the shear span to depth ratio (a/d). Chandra's experimentation involved specimens with a/d values of 0.625 and 1.22, revealing a notable increase in load carrying capacity as a/d decreased. Attiya and Mohamad-Ali explored three a/d ratios (0.5, 0.7, and 1), showing a decrease in load carrying capacity to 358 kN, 292 kN, and 235 kN respectively. Another researcher examined corbel samples with a/d ratios of 0.4 and 0.8, demonstrating a decrease in load carrying capacity from 63 kN to 49 kN respectively [7].

2.2 The Effect of Cover Area with CFRP on the Load Carrying Capacity

Al-Fadhli [18] reported of various reinforced concrete corbel specimens were tested with different configurations of Carbon Fiber Reinforced Polymer (CFRP) strengthening. The specimens included a control specimen labeled as B Control, along with specimens strengthened with horizontal CFRP in different layers (1, 2, or 3), denoted as B(H1), B(H2), and B(H3) respectively. Additionally, specimens with full wrap horizontal CFRP in one, two, or three layers were labeled as B (H1F), B (H2F), and B (H3F) respectively. Furthermore, a specimen with six vertical full-wrapped CFRP (three per each side) was denoted as B (V6F). The CFRP used had a thickness of 0.13mm, a width of 40mm, an ultimate tensile strength of 3.5 GPa, and a modulus of elasticity of 238 GPa. The shear span is 125mm with shear span to depth ratio is equal to 0.625. These specimens were part of the investigation to evaluate the effectiveness of different CFRP strengthening configurations in enhancing the load-carrying capacity of RC corbels.

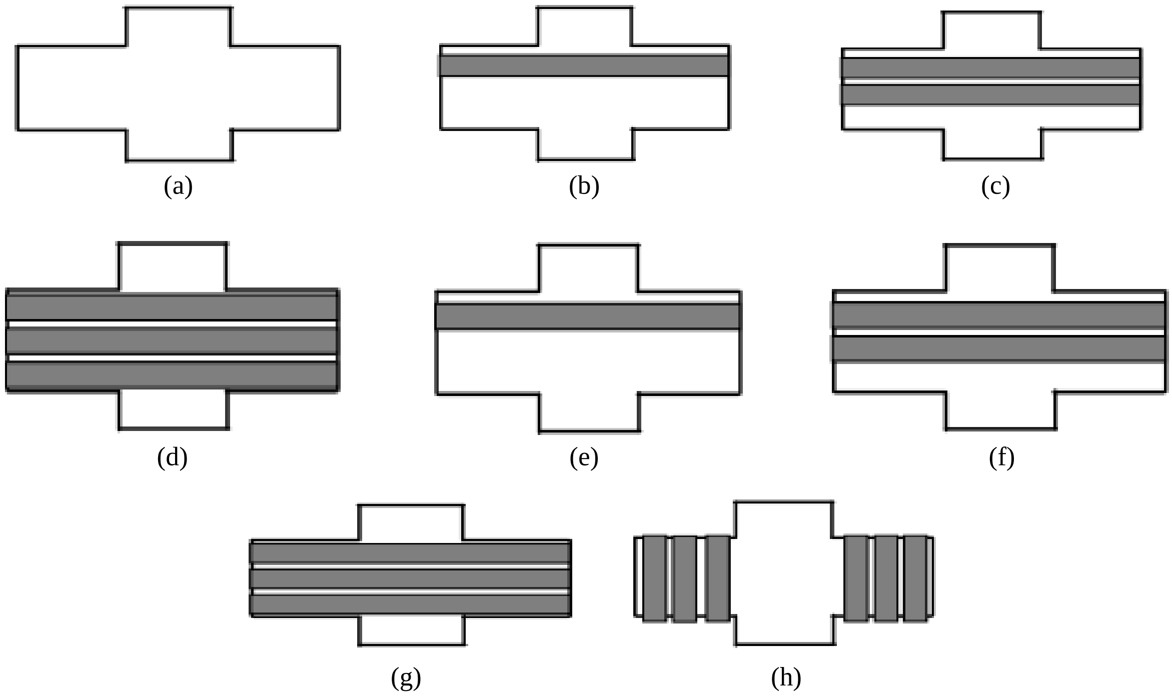
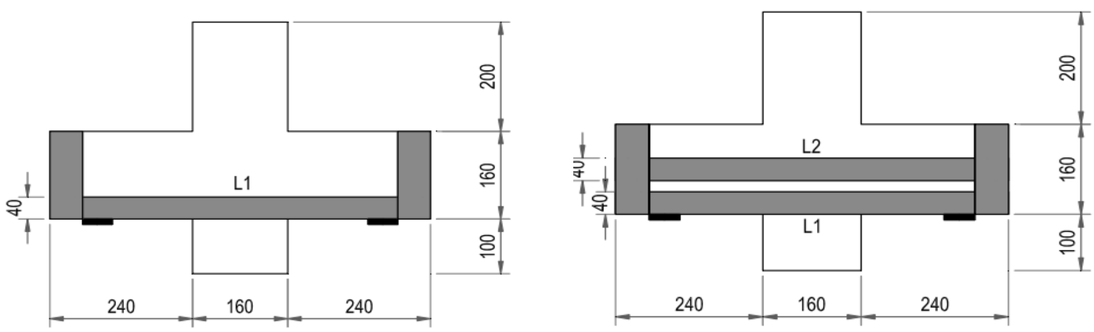
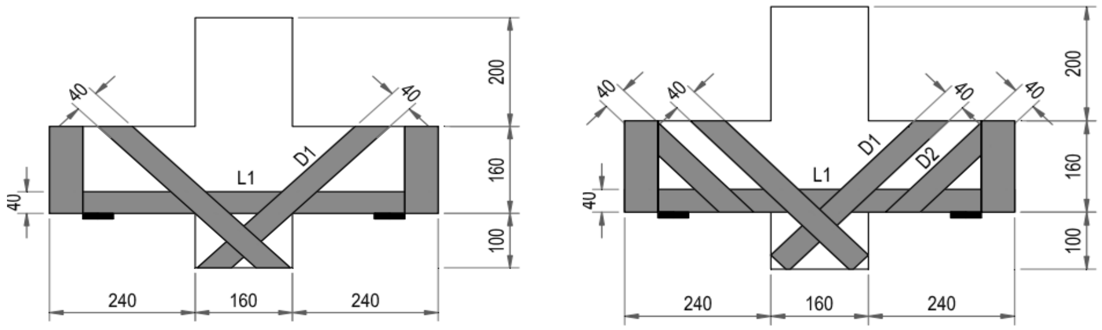


Figure 7. Strengthened corbels details (a) Control; (b) 1layer; (c) 2 layers; (d) 3 layers; (e) 1layer full wrap; (f) 2 layers full wrap; (g) 3 layers full wrap; (h) Six vertical full-wrapped CFRP [18]



(a) (b)

Figure 8. Strengthened corbels details (a) 1 horizontal and 2 vertical CFRP; (b) 2 horizontal and 2 vertical CFRP;

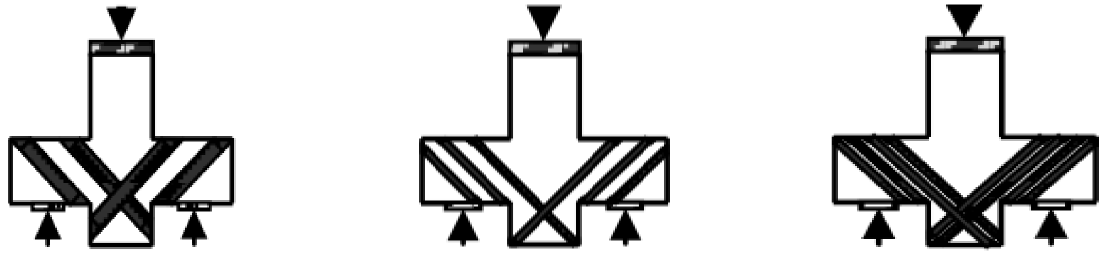


(c) (d)

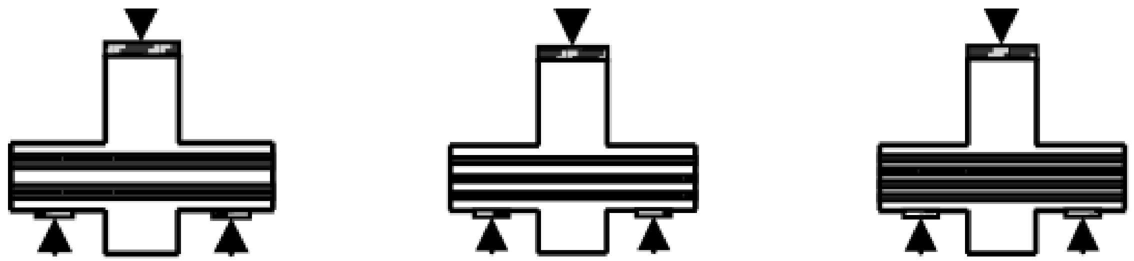
Figure 8. (cont.) (c) 2 diagonal and 2 vertical CFRP; (d)1 horizontal 4 diagonal and 2 vertical CFRP [19]

El-Maaddawy, T.A. and E.-S.I. Sherif [19] Reported various reinforced concrete corbel specimens were tested with different configurations of Carbon Fiber Reinforced Polymer (CFRP) strengthening. The specimens included a control specimen labeled as B-NF Control, which had a thickness of 0.381mm and a modulus of elasticity of 65.4 GPa. Additionally, specimens strengthened with two CFRP strips were denoted as B-2L, with a similar thickness and modulus of elasticity as the control specimen. Another configuration, B-2L-2S, involved two CFRP strips horizontally placed. Furthermore, specimens labeled as B-2L-2D and B-2L-4D featured two CFRP strips in diagonal configurations, with the latter having four CFRP strips diagonally placed. All these specimens had a thickness of 0.381mm and a modulus of elasticity of 65.4 GPa. The purpose of these tests was to assess the effectiveness of different CFRP strengthening layouts in improving the load-bearing capacity of reinforced concrete corbel.

Attiya and Mohamad-Ali [20] represented reinforced concrete corbel specimens were tested with different Carbon Fiber Reinforced Polymer (CFRP) strengthening configurations. The study included a control specimen labeled as CONT1. Additionally, specimens strengthened with inclined CFRP strips were denoted as CIS2, CIS3, and CIS4, with widths of 36mm and 18mm. The specimens have compressive strength of 36.7, 38.5, and 38.5 MPa respectively. Furthermore, specimens with horizontal CFRP strips were labeled as CHSR2, CHSR3, and CHSR4, with widths of 36mm and 18mm. These specimens exhibited compressive strength of 39.15, 39.15, and 36.7 MPa respectively. The study aimed to evaluate the effectiveness of different CFRP strengthening configurations in enhancing the load-carrying capacity of reinforced concrete corbels.



(a) (b) (c)



(d) (e) (f)

Figure 9. Strengthened corbels details by (a) 2 inclined CFRP 36mm; (b) 3 inclined CFRP 18mm; (c) 4 inclined CFRP 18mm; (d) 2 horizontal CFRP 36mm; (e) 2 horizontal CFRP 18mm; (f) 4 inclined CFRP 18mm [20]

Figure 10 demonstrates a clear trend where an increase in the cover area of CFRP results in a higher percentage of load carrying capacity enhancements for RC corbels. The data points show a progressive improvement in load capacity enhancement as the cover area of CFRP is increased from 7% to 28% for different strengthening configurations. The graph indicates that full wrap configurations of CFRP (1 horizontal full wrap, 2 horizontal full wrap, and 3 horizontal full wrap) generally lead to higher load capacity enhancement percentages compared to partial CFRP applications. The Six vertical full-wrapped CFRP configurations show the highest load capacity enhancement percentage among the tested configurations, reaching 71% improvement when cover area CFRP 28%. This analysis suggests that increasing the cover area of CFRP, especially through full wrapping configurations, can significantly enhance the load-carrying capacity of RC corbels [18].

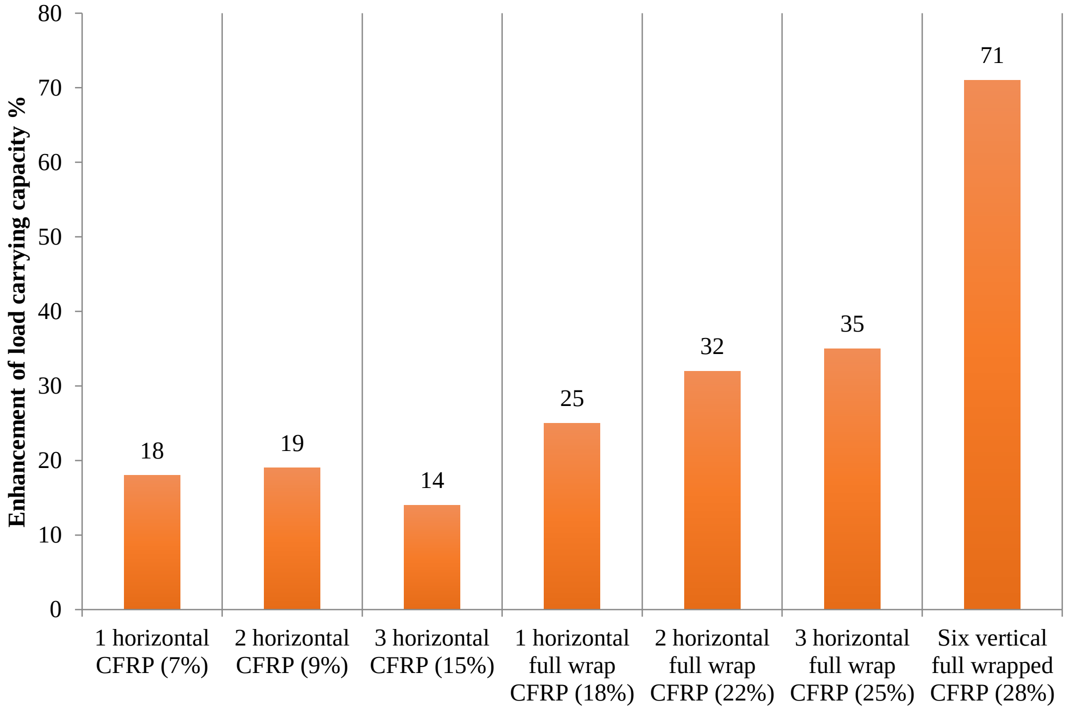


Figure 10. Load carrying capacity enhancement % based on cover area of CFRP

Figure 11 provides a comparison of load capacity enhancement percentages for different cover area, widths and orientations of CFRP strengthening applied to RC corbels. The graph shows variations in load capacity enhancement based on the width and orientation of CFRP, with inclined and horizontal configurations being evaluated. The data points reveal that wider CFRP widths generally result in higher load capacity enhancement percentages, with 18mm width 4 inclined CFRP and 18mm width 4 horizontal CFRP showing the highest enhancement percentages in the graph. The graph highlights the importance of considering the width and orientation of CFRP when designing strengthening strategies for RC corbels to achieve optimal load capacity enhancement [20].

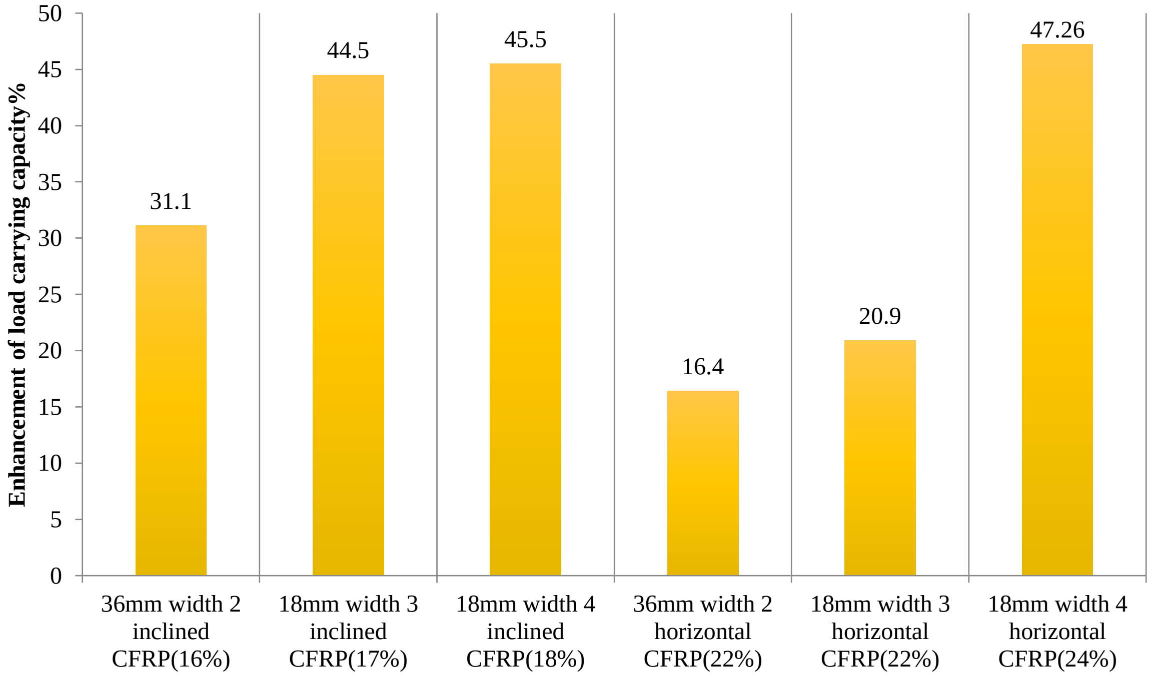


Figure 11. Load carrying capacity enhancement % based on cover area of CFRP

3. RESULT AND DISCUSSIONS

Chandra reported when reinforced concrete corbels are externally wrapped with carbon fiber reinforced polymer, experimental results show a notable increase in their ultimate load-carrying capacity. However, these strengthened corbels often cannot recover their full design capacity, primarily due to the limitations posed by the pre-existing conditions of local failure. The effective strengthening is 2 layers of CFRP by full wrapping with value of 780 kN. Also, the load capacity enhanced by 15, 42 and 72% for specimens 2-layer CFRP up to column interface, one-layer CFRP full wrap and 2-layer CFRP full wrap respectively, as shown in Figure 12. The effectiveness of the CFRP retrofit and the increase in load-carrying capacity vary based on factors such as the application method of the CFRP and the geometric placement of the load-bearing pad. Despite these variables, CFRP wrapping has been proven to be a feasible and effective method for enhancing the structural performance of RC corbels [5].

Shakir and Abdlsaheb revealed that RC corbels strengthened by CFRP either horizontally or diagonally. The strengthened method returned the full capacity of the corbels and the capacity increased from 287 kN to 415kN for applying CFRP horizontally and 420 kN when CFRP applied in 35 degree [21]. Neupane et al. reported when RC corbels are externally wrapped with CFRP, the results show a significant increase in their ultimate load-carrying capacity. The effective strengthening is 2 layers of CFRP by full wrapping with 200mm overlay and the load carrying reached to 788.7 kN while the control sample is about 458.4kN. The quality of the CFRP strengthening and the increase in load-carrying capacity are depending on factors such as the application method of the CFRP and the geometric placement of the load-bearing pad [6].

Moahmmed and Attia conducted on reinforced concrete corbels enhanced with Carbon Fiber Reinforced Polymer strips demonstrated significant improvements in load carrying capacity. Strengthened corbels, particularly those using an inclined CFRP strip technique, showed an increase in ultimate load capacity, with stiffer load-deflection responses compared to control specimens. The highlight of the effectiveness of CFRP as a strengthening by 36mm width of inclined CFRP which is 430 kN with comparing to control specimen is 292 kN. In addition, the ultimate load capacity improved by 47.26% for specimens which is diagonally wrapped by 36mm width of CFRP while the load enhances only by 16.4% when wrapped horizontally. When the width of CFRP reduced to 18mm the load enhancement reaches to 44.5 and 45.5% when the corbels wrapped diagonally and the load enhancement decreased to 31.1 and 20.9 % respectively, as shown in Figure 12 [20].

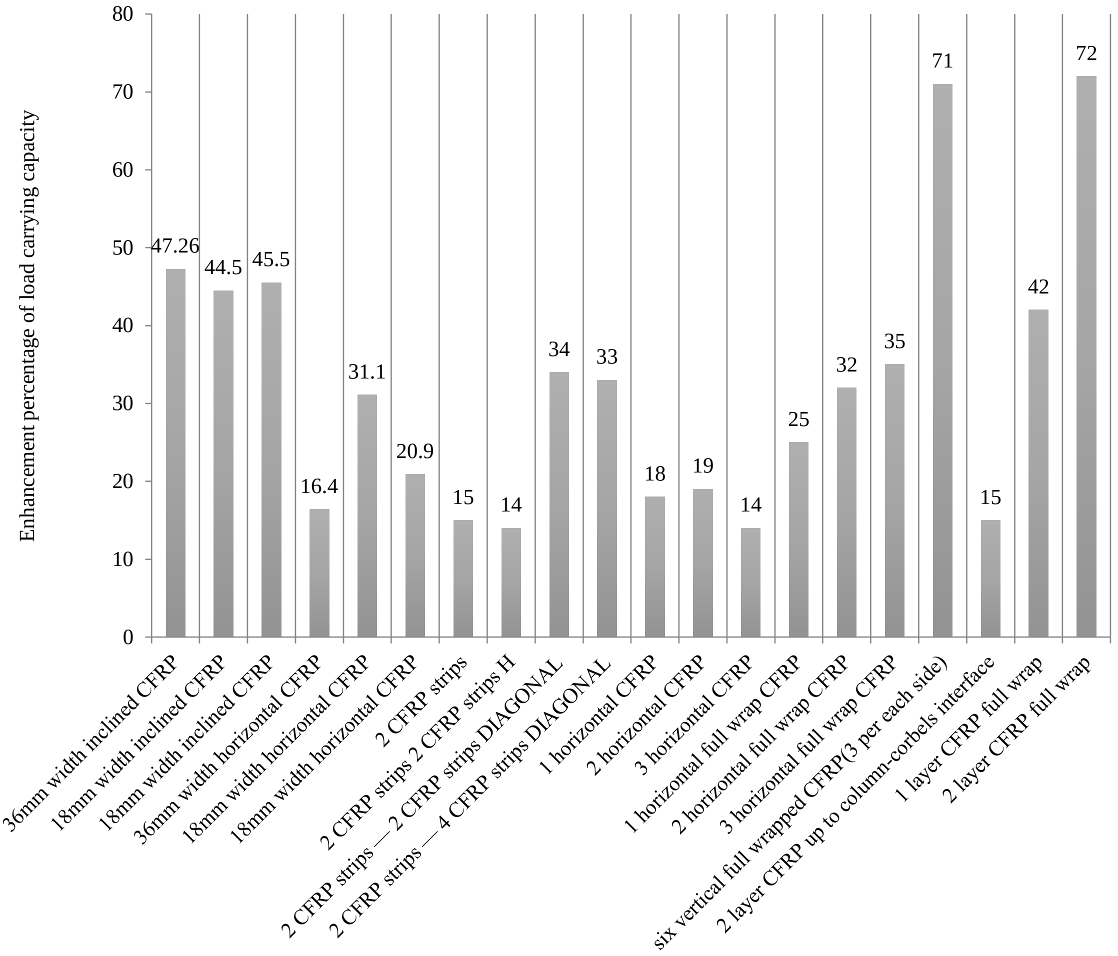


Figure 12. Load carrying capacity versus different strengthening technique

Al Fadhil showed the significant findings on enhancing the load-bearing capacity of reinforced concrete corbels. The study confirms that the ultimate load capacity of RC corbels is considerably increased when they are reinforced with a combination of carbon fiber-reinforced polymer. Specifically, increasing the layer of CFRP in the corbel results in a higher ultimate load sustainability. Additionally, when external CFRP sheets are applied, an even greater increase in ultimate strength is observed. The research provides empirical evidence by external CFRP sheets can improve the ultimate load capacity of RC corbels by approximately 35% when the sample full wrapped by 3 layers of CFRP, as shown in Figure 12 [18].

El-Maaddawy and Sherif reported that concrete corbels retrofitted with carbon fiber-reinforced polymer sheets yielded significant results. External CFRP reinforcement on concrete corbels enhanced load capacity by up to 34% as demonstrates in Figure 12. However, the benefit of CFRP decreased as the amount of internal steel reinforcement increased. Applying primary CFRP sheets parallel to steel rebars lessened steel strains and boosted yield and ultimate loads, but the addition of secondary CFRP sheets at mid-height did not enhance strength. Diagonal CFRP reinforcement limited shear crack expansion, leading to a higher load capacity [19].

4. CONCLUSIONS

Reinforced concrete corbels are crucial components in concrete structures, serving as short cantilevers to provide support for a range of pre-cast and pre-stressed structural elements. The following key elements may be used to outline the conclusion on the strengthening of reinforced concrete corbels utilising carbon fibre reinforced polymer:

- The application of CFRP significantly increased the load-bearing capacity of reinforced concrete corbels by up to 35% as compared to specimens without CFRP reinforcement.
- The use of CFRP wraps significantly improves the shear strength of reinforced concrete corbels and successfully prevents abrupt brittle failures, while also enhancing the overall ductility of the corbels.
- This study demonstrates that increasing the CFRP cover area, especially via complete wrapping configurations, can significantly improve the load-carrying capability of RC corbels. For example, the six vertical full-wrapped CFRP designs show the highest load capacity increase percentage among the studied configurations, with a 71% improvement when the CFRP wrap is 28% of the corbel area.
- CFRP reinforcement has been shown as a successful technique for enhancing the shear strength of reinforced concrete corbels. The extent of load improvement varies based on parameters such as the number of layers, overlap length, and the direction of wrapping of CFRP sheets.

ACKNOWLEDGEMENT

The authors would like to thank the Civil Engineering Department, College of Engineering, University of Sulaimani, for providing the facilities for this investigation.

AUTHOR CONTRIBUTIONS

Mohammed A. Ali: Conceptualization, Methodology, Data curation, Writing- Original draft preparation
Ferhad Rahim Karim: Supervision, Writing- Reviewing and Editing

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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