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Experimental Study of the Behavior of GFRP Reinforced Concrete Corbels

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ABSTRACT

Lately, there has been a growing use of FRP rebars (fiber reinforced polymer rebars) in structural components. To understand the complex behavior of these structures under loading, experimental studies are necessary. This article presents an experimental analysis of four double-sided concrete corbels reinforced with glass fiber-reinforced polymer (GFRP) bars and no web reinforcement, focusing on the effects of longitudinal reinforcement ratios and shear span to effective depth ratios (a/d) on structural performance. Two a/d ratios (0.7 and 1.0) and two values of longitudinal GFRP reinforcement ratios ($\rho_f = 0.56\%$ and $\rho_f = 0.87\%$) were tested to compare the shear behavior of the corbel specimens. The failure modes, stiffness, load-displacement curves, and diagonal strut mechanism are discussed. The results reveal that the splitting mode of failure and the diagonal strut mechanism become dominant once inclined cracks appear. While both the a/d ratio and GFRP reinforcement ratio influence the behavior of GFRP-reinforced concrete corbels, the a/d ratio has a more pronounced effect on shear resistance, whereas the GFRP reinforcement ratio has a lesser impact on shear strength. Additionally, the ACI 440.1R-15 guidelines for predicting the shear strength of GFRP-reinforced concrete corbels were found to provide overly conservative estimates.

1 Introduction

Nowadays, the use of Fiber Reinforced Polymer (FRP) bars as an alternative for traditional steel rebars is increasingly attracting the attention of researchers worldwide. Additionally, this type of reinforcement is becoming more widely used to replace steel in concrete structures in certain special environments. This is because FRP offers superior corrosion resistance

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compared to steel bars, particularly when concrete structures are subjected to harsh environmental conditions. Researchers have widely published studies on the flexural behavior of FRP reinforced concrete (RC) beams in recent years [1-5]. These studies indicate that FRP RC beams have greater load-bearing capacity but tend to exhibit higher deflection and larger crack widths compared to conventional steel- RC beams. Moreover, since FRP lacks yielding, which can result in sudden brittle failure without warning, appropriate measures must be implemented to mitigate this risk.

Many investigations have been undertaken on the shear performance of slender beams (with a shear span to effective depth ratio, $a/d \geq 2.5$) and deep beams reinforced with FRP bars. For slender FRP-RC beams, Mukhtar and Dewfall [6] reported that CSA S806-12 standard [7] for design has better accuracy than the guidelines of ACI 440-15 [8]. This is because it incorporates sufficient factors affecting the shear performance of slender concrete beams reinforced with FRP rebars. Meanwhile, for deep beams with $a/d < 2.5$, the standards and guidelines mentioned above generally do not predict the experimental results well. This may be because, for deep beams, the direct load transfer mechanism is much more dominant compared to other mechanisms. This mechanism is referred to as arch action which forms inclined struts between shear cracks and a tie in the tensile region of the beam. To improve the accuracy of shear capacity predictions for deep beams, many researchers have emphasized the shear-moment interaction by incorporating a multiplier [9, 10]. This interaction is represented by the a/d ratio, which is taken as 1 as the lower limit. This is due to the inability to use plane section analysis, which is typically replaced by a strut-and-tie approach. A recent study by Abu-Obaida et al. [11] investigated double-sided GFRP RC corbels, focusing on a/d ratios of 1.0 and 1.5. The experimental results indicated two main failure modes in the GFRP corbels: diagonal compression failure and concrete crushing at the top beam-column junction caused by the bending moment. However, the review highlights that experimental works have not yet examined FRP-reinforced beams or corbels with a/d ratios below 1.0, which can be encountered in industrial building structures or bridge structures.

Based on the issues analysed above and the gaps identified, this paper reports the experimental findings of four concrete corbels longitudinally reinforced with GFRP bars without vertical shear reinforcement. The experiments aim to clarify the effects of the GFRP longitudinal reinforcement ratio and the a/d ratio on the performance and shear resistance of the corbels.

A total of two sets of GFRP RC corbels having a -to- d ratios of 1.0 and 0.7, respectively, were manufactured and tested. Each set contained two corbels with different longitudinal reinforcement ratios. The findings of this study address existing gaps in the literature, contributing to a deeper understanding of how these parameters influence the performance of GFRP RC corbels.

2 Experimental program

In this research, four double-sided GFRP RC corbels were manufactured and loaded until failure to assess the impact of the a/d ratio and the tensile GFRP reinforcement on the shear behavior and strength of the corbels. All specimens were initially designed based on ACI 318-19 [12]. Four GFRP bars, each with a diameter of 10 mm or 12 mm, were utilized for tensile reinforcement in all the tested corbels. However, no stirrups were placed in the investigated span of the beam where shear failure was anticipated. On the opposite side of the beam, it was reinforced with two-legged steel stirrups spaced 75 mm apart to safeguard this section from damage during testing. The longitudinal GFRP reinforcement in the beam was configured in two layers, featuring a 15 mm concrete cover and a 15 mm interlayer spacing between the GFRP layers. The geometry and reinforcement specifications of the tested corbels are presented in Fig. 1 and Table 1. The reinforcement cage is shown in Fig. 2.

Notes: The corbel's ID includes the character "C" for corbel, 0.56 (or 0.87) for the tensile GFRP reinforcement ratio, and the last number (150 or 210) for the shear span; d is the effective height of the corbel; G denotes GFRP; A_f is the area of tensile GFRP bars, and $\rho_f = A_f/(bd)$ is GFRP reinforcement ratio.

The mean compressive cube strength of concrete for each corbel was evaluated by testing five cubes on the same day as the corbel test as shown in Table 2. The GFRP rebars used in this research have a tensile strength (f_{fu}) and Young's modulus (E_f) of 970 MPa and 44.3 GPa, respectively, as provided by the manufacturer.

The corbels were tested on a testing machine with 1000 kN maximum capacity. The load was gradually applied at a rate of 0.8-1.2 kN/sec. During the testing process, the strain in the longitudinal GFRP rebar and on the outermost

compressive concrete face were recorded using strain gauges SG1 and SG2, respectively. Additionally, the deflection of corbels was measured using an LVDT. Fig. 3 shows the complete experimental setup.

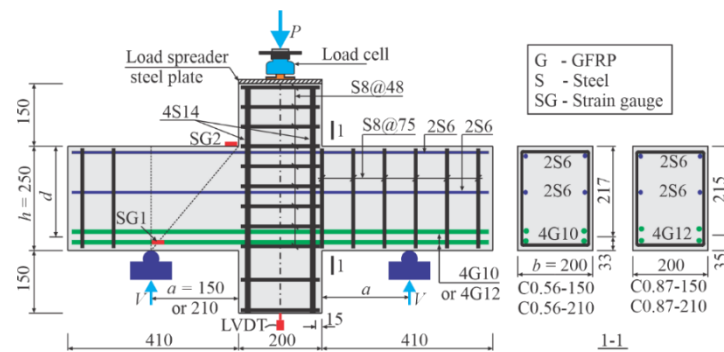


Fig. 1 – Configuration of the testing corbels and loading scheme.

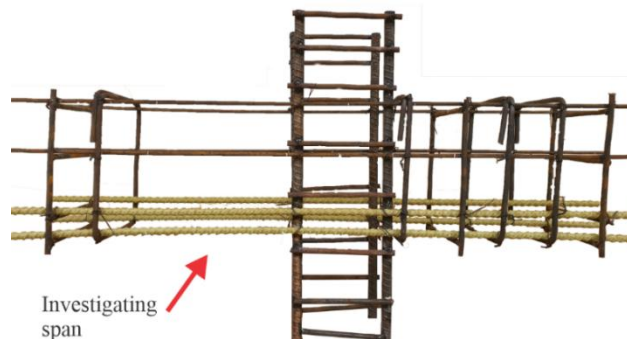


Fig. 2 – Reinforcement cage

Table 1 – Details of tested corbels.

Corbel's ID	Geometry, mm					Tensile reinforcement		
	b	h	d	a	a/d	Bar	A_f, mm^2	$\rho_f, \%$
C0.56-150	200	250	217	150	0.7	4G10	246	0.56
C0.56-210	200	250	217	210	1.0	4G10	246	0.56
C0.87-150	200	250	215	150	0.7	4G12	374	0.87
C0.87-210	200	250	215	210	1.0	4G12	374	0.87



Fig. 3– General testing arrangement

3 Test results and observations

3.1 Cracking patterns of the specimens and failure modes

All corbel beams were subjected to uniform loading until complete failure. During the loading process, the first flexural crack caused by the bending moment appeared at the beam-column connection interface at a load ($P_{cr,f}$) ranging from 31.4% to 37.3% of the maximum load (Table 2). As the load increased further, these vertical cracks propagated upwards, and inclined cracks began to form. The main inclined crack developed at a load ($P_{cr,i}$) ranging from 31.4% to 41.9% of the maximum load (Table 2). At the peak load (P_p), the primary inclined crack developed towards the load point, leading to shear failure. The shear failure split the corbel into two parts with the crack pattern shown in Fig. 4. All tested corbels failed due to diagonal splitting, which connected the load point and the beam-column connection interface.



a) Specimen C0.56-150



b) Specimen C0.56-210



c) Specimen C0.87-150



d) Specimen C0.87-210

Fig. 4–Failures of the corbel specimens

Table 2 – Test results

Specimen's ID	$P_{cr,f}$ kN	$P_{cr,i}$ kN	P_p kN	R_m MPa	f_p mm	$K_{s,f}$ kN/mm	$K_{s,i}$ kN/mm	$K_{s,p}$ kN/mm	$K_{s,i}/K_{s,f}$	$K_{s,p}/K_{s,f}$	$V_{c,test}$ kN	$V_{c,theor}$ kN	$V_{c,theor}/V_{c,test}$
C0.56-150	102	130	310.0	52.8	2.17	268.4	224.1	142.9	0.83	0.53	155.0	13.6	0.09
C0.56-210	100	105	268.0	52.8	5.18	116.3	97.2	51.7	0.84	0.44	134.0	13.6	0.10
C0.87-150	125	149	363.2	48.2	2.04	245.1	229.2	178.0	0.94	0.73	181.6	16.1	0.09
C0.87-210	80	80	254.7	48.2	2.90	186.0	186.0	87.8	1.00	0.47	127.4	16.1	0.13

3.2 Load-deflection curves

The load versus deflection relationships of tested specimens are depicted in Fig. 5. Before flexural cracks develop, the beams remain intact, the deflection of the beams in each pair is identical and does not depend on the shear span. Once flexural cracks form, the beams' flexural rigidity diminishes, particularly in beams with longer shear spans. This reduction is evident in the altered slope of the load-deflection curve. At the peak point, the deflection of the samples (f_p) with a 210 mm shear span ($a/d = 1.0$) is significantly greater than that of samples with a 150 mm shear span ($a/d = 0.7$). Specifically, the peak deflection ratio for the 210 mm shear span sample, compared to the 150 mm shear span samples, is 2.39 for the C0.56-i sample and 1.42 for the C0.87-i sample (see Table 2).

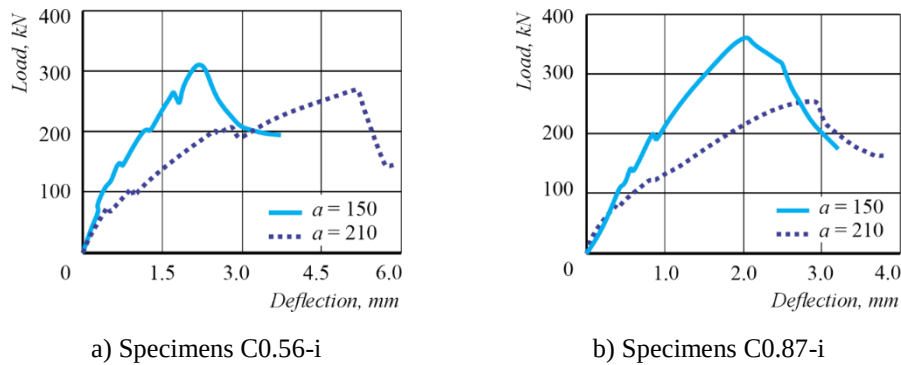


Fig. 5 – Load versus deflection curves of tested corbels

To improve insight into the nonlinear performance of GFRP RC corbels, the secant stiffness of the tested specimens at characteristic points, such as the flexural crack point ($K_{s,f}$), main inclined crack point ($K_{s,i}$), and peak point ($K_{s,p}$) was evaluated (Table 2). As shown in Table 2, at all characteristic points, the secant stiffness of corbels with an a -to- d ratio of 0.7 is higher than that of corbels with an a -to- d ratio of 1.0 in both pairs, C0.56-i and C0.87-i. With increasing applied load, the secant stiffness of the test specimens gradually decreases, and the rate of stiffness reduction is directly proportional to the increase in shear span (a/d). For the C0.56-150 specimen, at the point of appearance of flexural cracks and the peak point, the secant stiffness decreases by 1.2 times and 1.88 times, respectively, compared to the secant stiffness at the point of appearance of flexural cracks. For the specimen C0.56-210, the corresponding values are 1.2 and 2.25 times. Due to the contribution of longitudinal reinforcement, the decrease rate in secant stiffness of specimens C0.87-i with increasing external load is lower than that of specimens with both ratios $a/d = 0.7$ and $a/d = 1.0$. Specifically, the $K_{s,i}/K_{s,f}$ and $K_{s,p}/K_{s,f}$ ratios of specimen C0.56-150 are 0.83 and 0.53, respectively, which are lower than those of specimen C0.87-150, which are 0.94 and 0.73 (Table 2). Regarding 210 mm shear span corbels, the corresponding values for specimen C0.56-210 are 0.84 and 0.44 in comparison with the values of specimen C0.87-210, which are 1.0 and 0.47.

3.3 Diagonal strut mechanism

The inclined strut mechanism is explained through the strain development measured at SG1. The development of tensile strain in the main rebars at the support was monitored by strain gauge SG1 as shown on Fig. 6. It is evident that the increase in strain only occurs when flexural cracks appear, and it significantly increases when inclined cracks form. Clearly, the formation of the inclined strut mechanism from the support to the top corner of the column-beam interface explains this.

The compressive strain on the outermost surface of the beam was measured using strain gauge SG2. It can be observed that for corbels with short shear spans ($a = 150$ mm), shear behavior is predominant, and the compressive strain in the concrete does not develop significantly. For beams with larger shear spans ($a = 210$ mm), in addition to shear behavior, flexural behavior is also significant. Consequently, the maximum compressive strain in these samples develops more strongly compared to the 150 mm shear span samples. Furthermore, at the point of failure, the maximum strain in the concrete of the beams has not yet reached the ultimate value. This confirms that the mode of failure of the corbel is diagonal splitting.

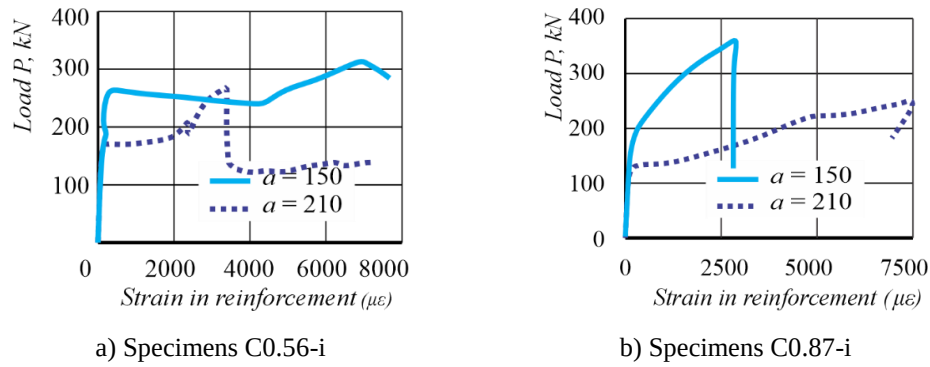


Fig. 6 – Development of tensile strain in main GFRP rebars (SG1)

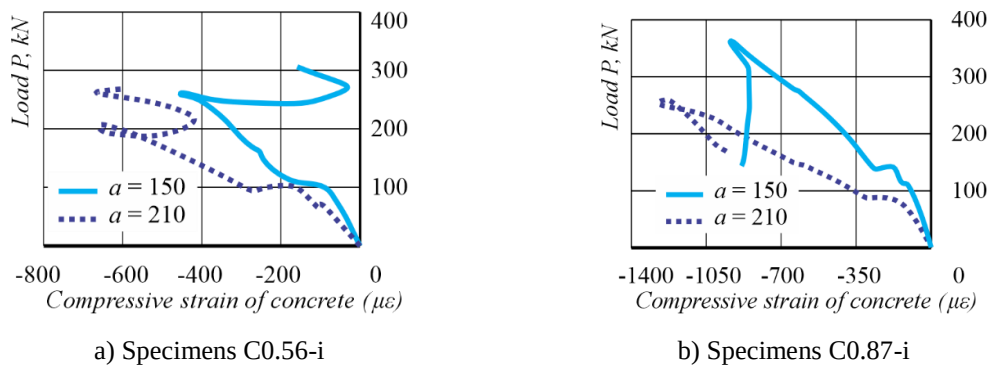


Fig. 7 – Development of maximum compressive strain on the outermost surface of the beam

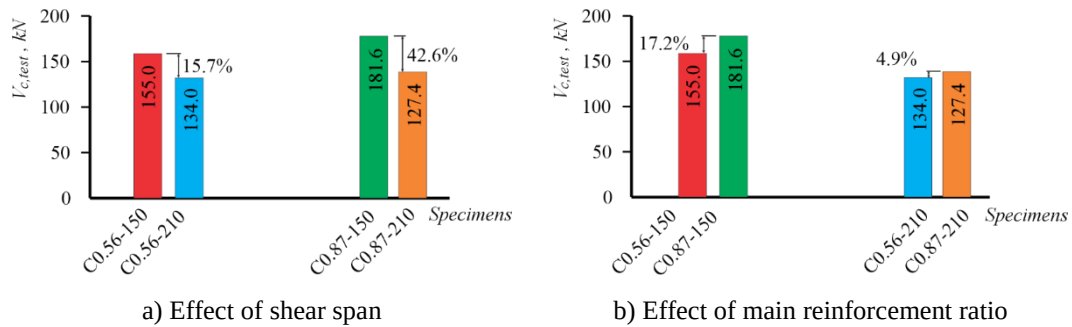


Fig. 8 – Comparison load load-carrying capacities of tested corbels

The shear resistance of the tested corbel specimens ($V_{c,test}$) is determined as the reaction corresponding to the maximum load and is shown in Table 2. Fig. 8 presents a comparison of the shear strengths of the tested GFRP RC corbel specimens. In Fig. 8a, it can be seen that decreasing the a/d ratio from 1.0 to 0.7 (the shear span changes from 210 mm to 150 mm) leads to an increase in the load-carrying capacity of corbels by 15.7% and 42.6 % for specimens C0.56-i and C0.87-i, respectively. The main reinforcement ratio also affects the shear strength of GFRP RC corbels. The comparison chart in Fig. 8b reveals that increasing the main GFRP reinforcement ratio from 0.56% to 0.87% results in a 17.2% increase in the shear strength of the beams with shear spans of 150 mm ($a/d = 0.7$). However, for corbels with $a/d = 1.0$, the impact of the main tensile GFRP reinforcement on shear capacity is insignificant. In fact, specimen C0.87-210 has lower shear strength than specimen C0.56-210. This may be due to the lower concrete strength of specimen C0.87-210 compared to that of specimen C0.56-210.

4 Design proposal

For designing short concrete beams reinforced with FRP, the author recommends using the design methods outlined in the ACI 440-15 [8]. In this approach, the shear resistance of the GFRP RC corbel $V_{n,theor}$ is the sum of the contributions from the concrete (V_c) and the stirrups (V_s). In the case of the tested corbels, there are no stirrups present, so the term V_s is omitted. Thus, the shear capacity of the corbel relies solely on the concrete's contribution to shear strength, calculated as follows:

$$V_{n,theor} = V_c = \left(\frac{5}{2}k\right)2\sqrt{f'_c}b_wd \quad (1)$$

where: b_w is the width of the web, and the parameter k is estimated as follows:

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \quad (2)$$

where $n_f = E_f/E_c$ is elastic modulus ratio; $E_c = 4734\sqrt{f'_c}$, MPa is the elastic modulus of concrete.

The theoretical shear capacity of the experimental corbels and its comparison with the experimental results are presented in Table 2. The comparison shows that the $V_{n,theor}/V_{c,test}$ ratio ranges from 0.09 to 0.13, indicating that the design approach based on ACI 440.1R-15 standards is overly conservative.

5 Conclusion remarks

This paper reports the experimental findings of four GFRP RC corbels with different a/d ratios and main tensile GFRP reinforcement ratios. Based on the experimental findings, several conclusion remarks can be reached:

As the a/d ratio decreases, there is a significant increase in the shear strength of the corbel. However, when the a/d ratio is 1, the tensile GFRP reinforcement ratio typically has little impact on the sample's shear strength.

For samples with a higher longitudinal GFRP reinforcement ratio, the secant stiffness ratio is greater compared to samples with a lower amount of longitudinal reinforcement.

The inclined strut mechanism forms immediately after flexural cracks appear, and the failure mode is diagonal splitting while the concrete in the compression zone of all corbels has not yet reached its ultimate strain.

The ACI 440.1R(2015) guidelines can be used to estimate the shear capacity of FRP reinforced concrete corbels without stirrups; however, the results tend to be overly conservative.

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