

Behavior of Normal and High Strength Reinforced Concrete Corbels Strengthened with Steel Plates

Marwa Abbas Fadel

Civil Engineering Department, Faculty of Engineering, Al-Mustansiriyah University, Baghdad, Iraq
eama015@uomustansiriyah.edu.iq (corresponding author)

Waleed Awad Waryosh

Civil Engineering Department, Faculty of Engineering, Al-Mustansiriyah University, Baghdad, Iraq
waleedwaryosh@uomustansiriyah.edu.iq

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ABSTRACT

Corbels are short cantilevered structural elements typically extending from walls or columns, characterized by a shear span-to-depth ratio (a/d) less than one. In this study, the structural performance of reinforced concrete corbels strengthened with externally bonded steel plates was evaluated under monotonic vertical loading. The experimental program included six reinforced concrete corbel specimens, each with dimensions of 250 mm span \times 150 mm width \times 250 mm depth. The investigation focused on three main parameters: concrete compressive strength, that is, 30 MPa for Normal-Strength Concrete (NSC) and 70 MPa for High-Strength Concrete (HSC), the presence or absence of steel plate reinforcement, and two a/d ratios (0.3 and 0.6). The results indicated that the use of steel plates significantly enhanced the structural behavior of the corbels, increasing the ultimate load capacity, crack resistance, and energy absorption. The specimens strengthened with steel plates also demonstrated improved ductility compared to the un-strengthened specimens. These findings confirm that the external steel plate reinforcement is an effective method for enhancing the mechanical performance of both NSC and HSC corbels under vertical loading.

Keywords-corbels; High Strength Concrete (HSC); Normal Strength Concrete (NSC); steel plate; monotonic vertical loading

I. INTRODUCTION

Corbels are structural elements that extend outward from columns or walls. They are commonly used in precast concrete structures to support the precast and prestressed beams, transferring loads to the vertical structural members [1–4]. Corbels can be constructed from a single piece of wood, concrete, or integrated into columns or walls. Structurally, they behave more like simple trusses or deep beams rather than typical flexural members, especially when the shear span-to-effective depth ratio (a/d) is small, typically around 1.0, which classifies them as deep beams. Unlike the conventional beams that fail in a ductile manner through bending, deep beams and, therefore, corbels fail in a more brittle fashion due to shear [5]. Consequently, corbels are primarily considered shear force transfer elements. The high load-bearing capacity of corbels is largely attributed to their low a/d ratio [6].

Previous studies have demonstrated that incorporating steel fibers into concrete corbels significantly affects their structural behavior [3, 4, 7–9]. Increased steel fiber content improves the fracture resistance, ductility, stiffness, and load-carrying

capacity [10]. Moreover, fiber-reinforced concrete corbels tend to fail more gradually, with failure typically occurring through either inclined shear or flexure [11, 12]. Steel plates are among the most commonly used materials for strengthening the reinforced concrete beams, particularly effective in enhancing both their flexural and shear capacities. With the growing demand for the repair, upgrading, and maintenance of the aging infrastructure, this reinforcement technique has drawn significant attention [13].

In [14], the Externally Bonded Reinforcement (EBR) technique was identified as one of the most widely adopted methods for strengthening the concrete structures. However, due to premature debonding, carbon fiber strips bonded directly to the surface of the concrete members using epoxy adhesive were unable to fully utilize the tensile capacity of Fiber-Reinforced Polymer (FRP) materials. In contrast, the Near-Surface Mounted (NSM) method has demonstrated the ability to better exploit the maximum tensile strength of such reinforcements. Authors in [15] investigated the application of carbon fiber textiles for enhancing the performance of short reinforced concrete corbels. The study examined the

mechanical behavior of four concrete corbels under various reinforcement configurations, including two with carbon fiber reinforcement and one with steel plate strengthening. The findings indicated that, compared to the steel plate bonding, fiber wrapping provided the most effective configuration, resulting in an 82% increase in failure load relative to the control specimen.

In [16], experimental and numerical analyses were conducted to evaluate the design of reinforced concrete brackets used to support central slabs in double-deck tunnels. These brackets, attached to the tunnel liner, are responsible for sustaining the entire load transferred from the central slabs. Consequently, an appropriate bracket design is essential to prevent the slab collapse, tunnel liner failure, and associated human and material losses. Full-scale loading tests were performed on bracket-attached tunnel liner specimens to verify the design, assess the safety margins, and determine the failure modes. Additionally, numerical models were developed to analyze the structural behavior and investigate the influence of bracket geometry on the structural capacity.

A macro-mechanical strut-and-tie model was proposed to study high-strength fibrous concrete corbels [17]. In this approach, fibers were employed to partially or completely replace horizontal stirrups. The study evaluated the effects of several parameters, including fiber volume fraction, fiber length and diameter, random fiber distribution, fiber High-Strength-Concrete (HSC) interface, shear span-to-depth ratio, and concrete compressive strength. The results indicated that increasing the fiber content, fiber aspect ratio, and concrete strength significantly improved the maximum vertical load-bearing capacity of the corbels.

In [18], eight reinforced concrete brackets strengthened through the utilization of various techniques were examined. The experimental program considered multiple strengthening configurations, including external, internal, and repair types, employing Carbon Fiber Reinforced Plates (CFRP), CFRP bars, and steel plates with varying orientations and dimensions. The strengthened samples were compared against a control specimen in terms of the load capacity, deflection, cracking behavior, and failure mode under static loading. It was concluded that the CFRP plate reinforcement notably improved the performance, with load-carrying capacity increases ranging from 32% to 124%. The highest enhancement was observed in the specimens with the orthogonal alignment of CFRP plates relative to the crack paths.

Another investigation focused on the NSM steel bar technique for strengthening and repairing damaged reinforced concrete corbels [19]. Three configurations were analyzed: horizontal, diagonal, and composite. The results demonstrated that this technique was particularly effective during the early loading stages. The diagonal system yielded the best performance in terms of cracking resistance and failure load, achieving increases of 166% and 95%, respectively, compared to the control. For specimens with 45% damage, the horizontal configuration achieved the highest failure load (99%), whereas the diagonal configuration was most effective (50%) for specimens with 65% damage.

The aim of this study is to investigate the structural behavior of reinforced concrete mill structures constructed using two types of concrete: NSC and HSC. In selected specimens, the eaves were strengthened with externally attached steel plates. The use of steel plate reinforcement was found to play a significant role in enhancing both the mechanical performance and geometric stability of the structural models. Additionally, the effect of steel plate strengthening on the compressive strength of the models was evaluated, highlighting notable differences between reinforced and unreinforced configurations.

II. RESEARCH SIGNIFICANCE

The previous studies utilized materials, such as steel fibers and carbon FRPs for strengthening eaves, which are costly, technologically demanding, and less accessible, while the current study employed steel plates, which are widely available, cost-effective, and easy to implement. Moreover, prior reinforcement methods often resulted in brittle failure due to the linear behavior of the reinforced elements, offering little to no warning before collapse. In contrast, the use of steel plates was found to produce a more ductile response, providing observable warning signs prior to failure. The results further indicated that the steel plate reinforcement significantly increased the load-bearing capacity of the models up to the point of failure. The present investigation was conducted to address existing knowledge gaps and provide valuable insights for developing general design criteria for steel plate-reinforced corbels subjected to vertical loading.

The results, demonstrated that the application of steel plates significantly enhanced the compressive strength and overall performance of reinforced concrete corbels, confirming the effectiveness of this method as a practical and reliable approach to corbel reinforcement.

III. EXPERIMENTAL INVESTIGATION

A. General

Six double-sided corbels were constructed with a constant depth of 250 mm and a column of 150 mm depth \times 200 mm width \times 650 mm length. Each specimen was designated based on a systematic coding scheme to reflect its key characteristics: section type (C: corbel), concrete type (N: for NSC, H: for HSC), steel plate strengthening (S: strengthened, 0: not strengthened), a/d (3 stands for 0.3 and 6 for 0.6), and loading type (M: monotonic load). The specimens were only subjected to vertical load and were divided in two groups according to the type of concrete, NSC and HSC (Table I).

TABLE I. DETAILS OF CORBEL SPECIMENS

Group	Specimen	Type of concrete	d/a	Strengthening
A (NSC)	CN06M	Normal strength	0.6	None
	CNS6M	Normal strength	0.6	Steel plate
	CNS3M	Normal strength	0.3	Steel plate
B (HSC)	CH06M	High strength	0.6	None
	CHS6M	High strength	0.6	Steel plate
	CHS3M	High strength	0.3	Steel plate

B. Materials Used

1) Cement, Fine Aggregates, and Coarse Aggregates

According to [20], ordinary Portland cement, cleaned natural sand, and 1.2 cm gravel were used during the test. Also the physical characteristics of the fine and coarse aggregates were found to meet the specifications outlined in [21] (Tables II, III).

TABLE II. CHEMICAL COMPOSITION OF CEMENT

Compound composition	Chemical composition	Percentage by weight	[20]
lime	CaO	60.74	-
Silica	SiO ₂	18.14	-
Alumina	Al ₂ O ₃	6.71	-
Iron oxide	Fe ₂ O ₃	2.9	-
Magnesia	MgO	1.28	<5.0%
Sulfate	SO ₃	2.09	<2.80%
Loss on ignition	L.O.I	2.25	<4.00%
Insoluble residue	I.R	1.25	-
Chloride	Cl	0.009	-
Tri calcium aluminate	C ₃ A	12.88	-
Total		98.95	-

TABLE III. PHYSICAL PROPERTIES OF CEMENT

Physical characteristics	Results	[20]
Specific surface area (Blaine method) (m ² /kg)	4678	(230 m ² /kg) lower limit
Setting time		
Initial setting time: (min)	125	≥45 min
Final setting time: (hour)	3:50	≥10 hour
Compressive strength (MPa)		
2-days	25	≥ 20
28-days	43	≥ 42.5

2) Steel Reinforcement

Regarding reinforcement, 12 mm diameter distorted steel bars served as the longitudinal reinforcing of the supporting shaft and the primary tensile reinforcement for the corbel, while 8 mm diameter distorted steel bars were employed as the shaft's connecting rods (Figure 1).

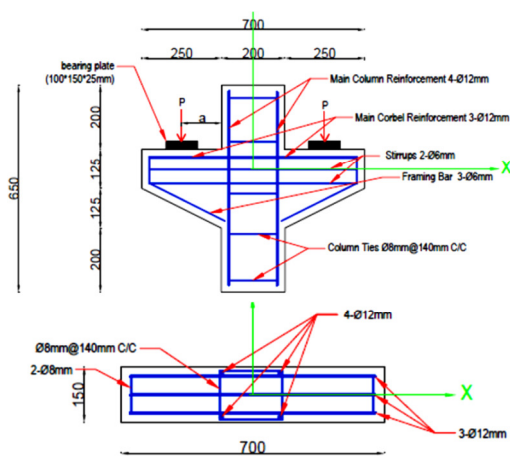


Fig. 1. Structure's yield strengths.

Additionally, 6 mm bars were used to make the frame and reinforcing bars. Three specimens for every bar size were evaluated utilizing ASTM C370 [22]. The structure's yield strengths were 498 MPa, 655 MPa, and 620 MPa.

3) Superplasticizer

A superplasticizer called High Water Reduction Agent (HWRA) made from poly-carboxylic ether was added to the mixture to create self-consolidating concretes. It is marketed under the trademark Glenium51, it is free of chlorides, and complies with ASTM C494 [23]. Moreover, it works well with any Portland cement and meets the global standards (Table IV).

TABLE IV. GENERAL CHARACTERISTICS OF GLENIUM51

Main action	Glenium51
Form	Viscous liquid
Color	Light brown
pH	6.60
Relative density	1.1 at 20°C
Chlorides	Free of chlorides
Transport	Not classified as dangerous
Viscosity	128 +/- 30cps at 20°C
Labeling	No hazard label is required

4) Silica Fume

Sika-microsilica, produced by Sika Company, was the kind of silica fume utilized in this study, which satisfies ASTM C1240 [24] physical and chemical requirements (Table V).

TABLE V. REQUIREMENTS OF SILICA FUME

Requirement	Test (%)	Specifications limits (ASTM C-1240) [24]
SiO ₂	86.460	> 85.00
Moisture content	0.680	< 3.00
LOI	4.020	< 6.00
Percent Retained on 45-µm	7	< 10
Specific surface, min, m ² /g	21	> 15

5) Steel Plate and Bolts

Steel plates measuring 60 mm in height, 70 mm in length, and 6 mm in thickness were utilized as exterior stiffeners in this investigation, with their characteristics being presented in Table VI.

TABLE VI. DETAILS OF STEEL PLATE AND BOLTS

Steel samples	Plates' thickness (mm)	Elongation %	Bonding technique	Yield stress (N/mm ²)	Ultimate stress (N/mm ²)
Steel plate	6 mm	9.34 %	Anchor bolts	364.44	455.56

The anchor bolt method was used to attach the plates (Figure 2).

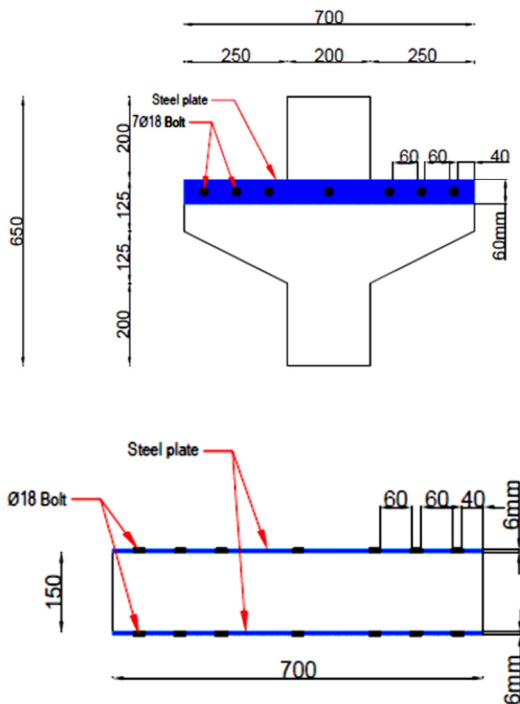


Fig. 2. Steel plate and bolt details.

the testing machine and adjusted in such a way that the supports, dial gauge, load arm, and centerline of the column were installed at their correct locations. The location of the applied load at the right and left side faces of the column, meaning the a/d varied from 0.3 to 0.6. The column of the corbel was under vertical load at its top end. The load was applied in an incremented manner at a range of 5 KN/stage until the failure occurred in the corbel (Figure 3).

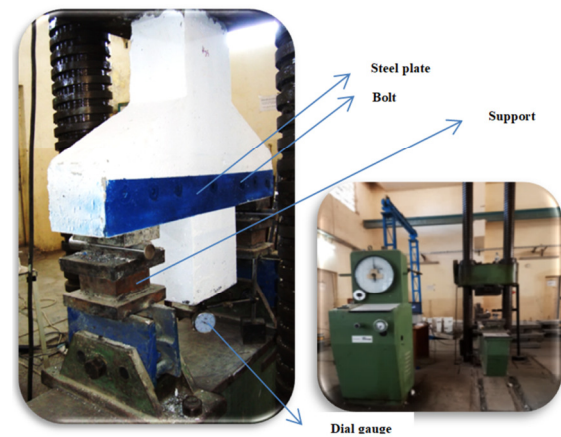


Fig. 3. Specimen test setup.

C. Mix Design

The weight-to-mix proportion was utilized to create two kinds of concrete: NSC, which was then submerged in water for 28 days and had a compressive strength of about 30 MPa, and HSC, which was immersed in water for 28 days and had a compressive strength of roughly 70 MPa. For the HSC, before mixing, the sand and gravel are added to the rotary mixer along with a 1/3 ratio of mixing water to get them wet. Maintaining the mixer in a clean, damp state without using water is crucial. The mixture is then stirred for 1 min. The following step involves adding 1/3 of water combined with 1/3 suitable plasticizer and mixing for a full min. At this point, cement and silica are added and mixed for 30 sec. Finally, for 90 seconds, the remaining water is progressively mixed with 2/3 of the superplasticizer, with the total mixing period lasting 4 min. The technique for the NSC samples is the same but does not include the use of superplasticizer and silica (Table VII).

TABLE VII. MIXING FEATURES

Cement type	Cement kg/m ³	Gravel kg/m ³	Sand kg/m ³	w/c	Superplasticizer (L/m ³)	Silica fume (kg/m ³)	Target strength MPa (f'c)
NSC	400	1200	600	0.45	—	—	30
HSC	585	1136	651	0.27	7	58.42	70

D. Test Settings

Push-off tests were conducted, utilizing the testing hydraulic machine of the laboratory of the Mustansiriyah University's College of Engineering with a total capacity of 3000 KN. The corbels were placed in an inverted position on

IV. RESULTS AND DISCUSSION

A. The Behavior of Corbels Specimens

During the initial stages of loading, all specimens exhibited high stiffness and load resistance up to the formation of the first crack. In this phase, the vertical displacement was minimal, and no visible cracking was observed. Once initial cracking occurred, the stiffness began to degrade, and the vertical displacements increased progressively. Flexural cracks were first observed on the tension face of the corbels near the column interface. As the loading continued, both the number and width of cracks increased until yielding of the tensile reinforcement or rupture of the steel bars occurred.

Following this, a nonlinear behavior became evident, with deflection increasing rapidly, indicating a further loss in stiffness. At advanced loading stages, diagonal shear cracks initiated near the support zones and propagated toward the column face. These shear cracks were more severe and wider than the earlier flexural cracks. Notably, the specimens strengthened with steel plates demonstrated improved ductility and delayed failure compared to their un-strengthened counterparts. Furthermore, no significant interfacial debonding or shear concentration was observed between the steel plate and concrete surface, suggesting effective stress distribution and bonding.

Three distinct failure modes were identified (Table VIII):

- Diagonal Shear Failure: Initiated by a flexural notch that developed prior to the diagonal splitting of the concrete. This crack originated at the bearing plate and extended toward the intersection between the corbel's sloped face

and the column shaft. Corbels with such cracking typically failed in shear within the compression zone.

- **Flexural Tension Failure:** This mode was observed at the junction between the corbel and column face after the fiber pull-out from the concrete matrix. It was characterized by large, vertically propagated cracks with significant width and depth.
- **Bending Stress Failure:** Occurred before the complete fiber pull-out, driven by the yielding of tensile reinforcement. This failure mode led to a gradual degradation in stiffness, preventing sudden shear collapse and allowing for more ductile behavior.

At initial loading, all corbels were crack-free. The first observable cracks occurred in the tension zone between the corbel and the column. These cracks propagated slowly along the interface between the bearing plate and the column flange until the second major crack formed.

TABLE VIII. EXPERIMENTAL ULTIMATE LOADS AND FIRST CRACKING OF CORBELS.

Specimen	Pcr (KN)	Pu (KN)	Failure mode
CN06M	101.5	406.5	Diagonal splitting
CNS6M	169	507.25	Flexural
CNS3M	207.5	588.75	Flexural
CH06M	219.44	658.5	Diagonal splitting
CHS6M	303.4	758.5	Flexural
CHS3M	426.25	852.5	Flexural, bending

The early-stage flexural crack preceded the diagonal splitting, progressing from the bearing plate toward the interface of the column face and the sloped corbel face. Corbels with this crack pattern tended to experience diagonal shear failure in the compression zone (Figure 4).



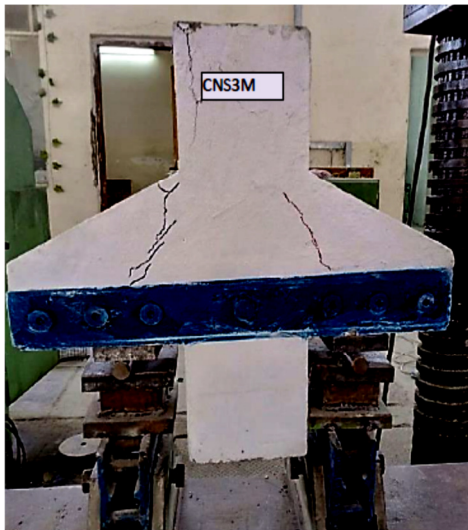


Fig. 4. Corbel patterns of cracks after testing.

B. Impact of Shear Span on Efficient Depth Proportion

In the current study, the influence of a/d on the cracking and ultimate load capacities of corbels was investigated by reducing the ratio from 0.6 to 0.3, in contrast to prior studies that adopted different a/d values [25, 26]. The results demonstrated that a reduction in the a/d ratio leads to a general increase in both the cracking and ultimate loads for corbels with identical properties, assuming that all other parameters remain constant. For corbels constructed with normal strength vibrated concrete and strengthened using steel plates, decreasing the a/d ratio resulted in an approximate increase of 22.78% in the cracking load and 16.06% in the ultimate load (Figure 5).

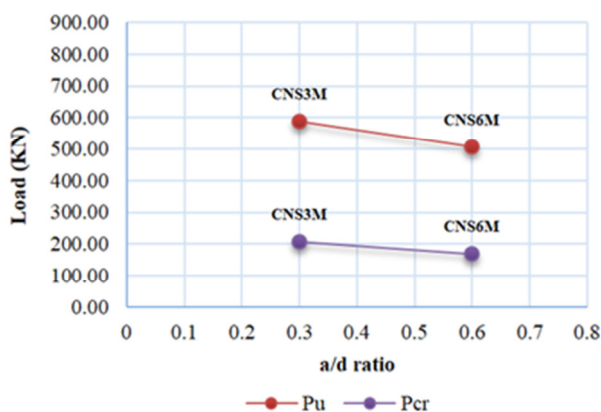


Fig. 5. a/d and cracking relation for NSC corbels strengthened by steel plates.

Similarly, corbels composed of HSC exhibited a 40.49% rise in the cracking load and a 12.39% increase in the ultimate load under the same conditions (Figure 6).

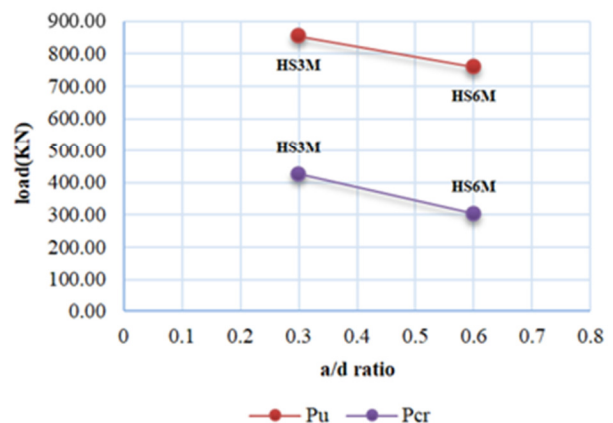


Fig. 6. a/d and cracking relation for HSC corbels strengthened by steel plates.

C. Influence of Concrete Compressive Strength

The compressive strength of concrete, along with the section dimensions and reinforcement ratio, represents a key parameter influencing the load-carrying capacity of reinforced concrete corbels [27-29]. The experimental results presented in this study highlight the significance of concrete compressive strength in enhancing structural performance. When the a/d was maintained at 0.6 and no steel plate strengthening was applied, the comparison between the specimens revealed that increasing the compressive strength led to a substantial improvement in the performance. Specifically, the increase in the ultimate load capacity between the specimen CN06M and the reference specimen CH06M was approximately 61.99%, while the increase in the cracking load was 49.53%. Similarly, for specimens CNS6M versus CHS6M and CNS3M versus CHS3M, the respective increases in the ultimate capacity due to higher compressive strength were 44.79% and 105.42%. This trend indicates that enhancing the concrete compressive strength contributes to improved cracking resistance and delays the onset of the first crack due to an increase in flexural stiffness.

The overall performance improvements in CH06M, CHS6M, and CHS3M specimens were approximately 116.73%, 79.52%, and 105.42%, respectively, compared to their control counterparts CN06M, CNS6M, and CNS3M (Figures 7-9).

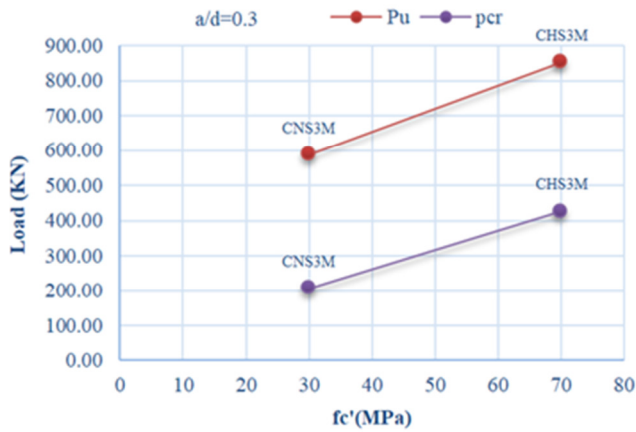


Fig. 7. Concrete compressive strength and corbel cracking in S3M samples.

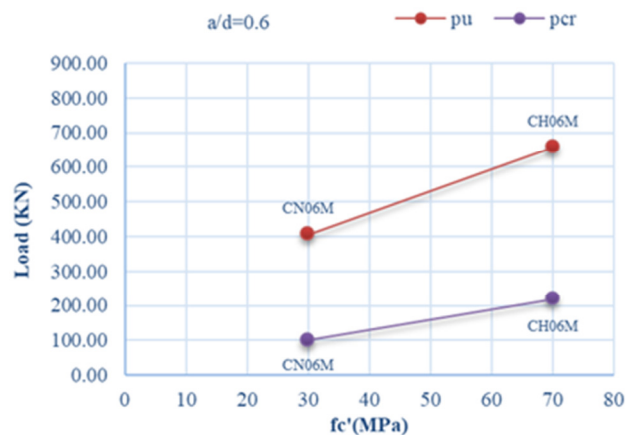


Fig. 8. Concrete compressive strength and corbel cracking in 06M samples.

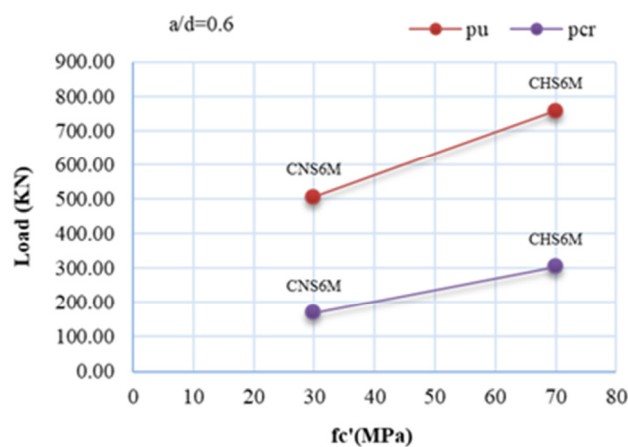


Fig. 9. Concrete compressive strength and corbel cracking in S6M samples.

D. Influence of Steel Plate on Cracking and Ultimate Loads

The use of steel plates as an external reinforcement technique proved effective in enhancing both the performance and strength of the tested corbel specimens. The application of steel plates not only increased the ultimate load capacity, but also contributed to delaying the onset of the initial cracking, indicating improved durability characteristics. The experimental results showed that the inclusion of steel plates led to an increase in the maximum load capacities by approximately 24.78% and 15.18%, and in the cracking loads by 66.91% and 38.26% for specimens CH06M, CHS6M, and CN06M, when the a/d was set at 0.6 (Figures 10, 11). Given the cost-effectiveness of the steel plates and the relative ease of installation compared to other strengthening materials, several researchers have proposed their use as a practical and economical solution for enhancing the structural behavior of reinforced concrete corbels.

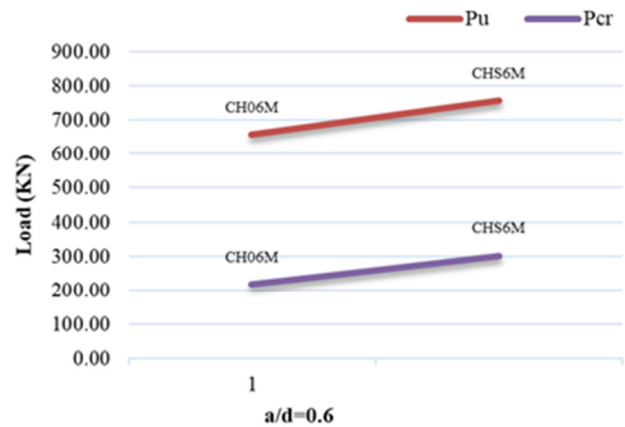


Fig. 10. Steel plate impact on max loads and cracking for HSC corbels.

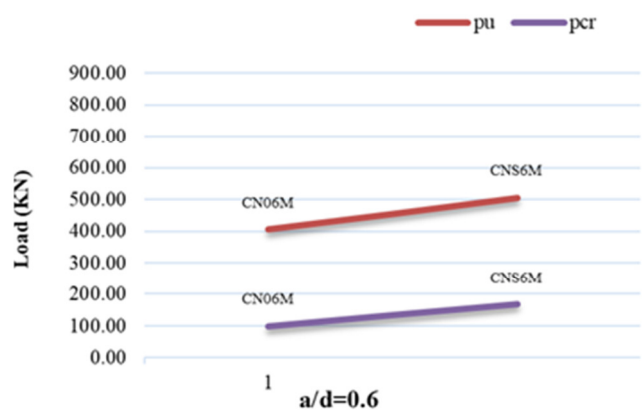


Fig. 11. Steel plate impact on max loads and cracking for NSC corbels.

E. Load Deflection Relationship

The testing of the specimens was terminated either upon visible specimen damage or when the applied load began to decrease due to a continuous increase in deflection. The measured displacement of the loading jack corresponded to the vertical deflection at the mid-point of the column supporting the twin corbels. The final ultimate loads recorded for the

specimens were 406.5 kN, 507.25 kN, 588.75 kN, 658.5 kN, 758.5 kN, and 852.5 kN for CN06M, CNS6M, CNS3M, CH06M, CHS6M, and CHS3M, respectively. In the early stages of loading, the load–deflection curves exhibited a linear trend with a nearly constant slope, indicating elastic behavior. As the loading progressed and initial cracking occurred, the response transitioned to a nonlinear behavior with varying slopes, which persisted until failure (Figures 12-16).

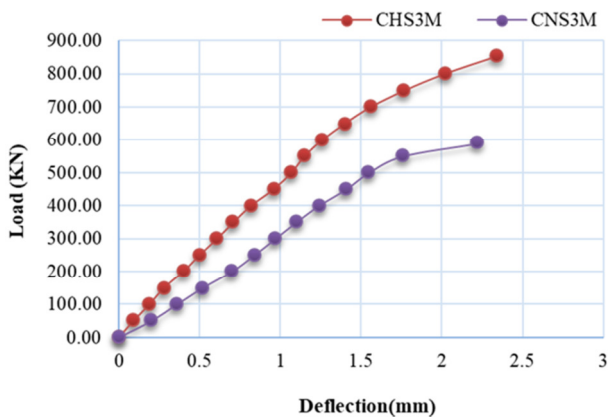


Fig. 12. Load-deflection response to corbels strengthened with steel plate and a/d ratio 0.3.

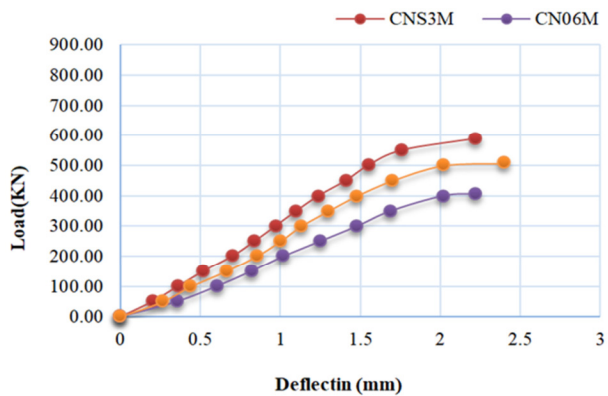


Fig. 13. The a/d proportion impact on the load-deflection response for NSC corbels.

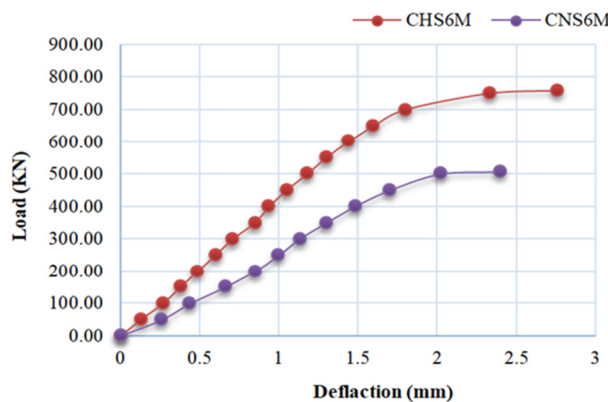


Fig. 14. Load-deflection response to corbels strengthened with steel plate and a/d ratio 0.6.

To analyze and represent the load–deflection data, a Bezier curve fitting approach was applied. This technique is suitable for approximating smooth, continuous shapes defined by discrete data points, particularly when the mathematical expression of the curve is complex or unknown. The Bezier fitting method was found to provide a reasonable approximation for the load–deflection curves exhibiting inflection points, meaning points of contra-flexure. However, in cases where the curves lacked inflection points, the method yielded less accurate representations [30, 31].

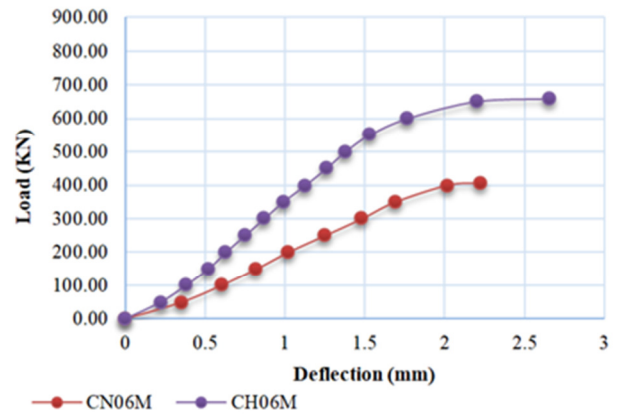


Fig. 15. The load-deflection response to corbels and a/d ratio 0.6.

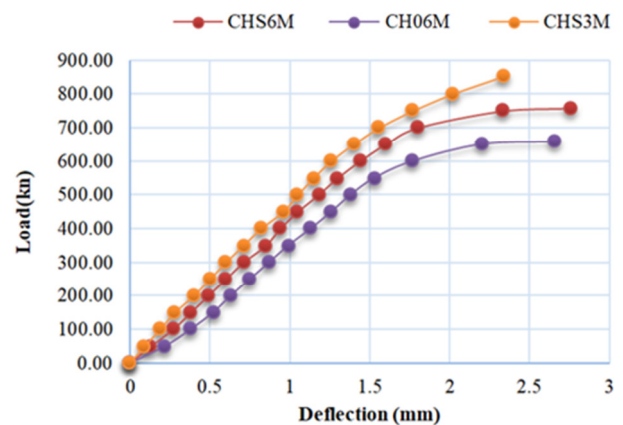


Fig. 16. The a/d proportion impact on the load-deflection response for HSC corbels.

V. CONCLUSIONS

The study examined how the steel plates influence the corbels reinforced with Normal-Strength Concrete (NSC) and High-Strength Concrete (HSC). The main conclusions drawn are:

- Increasing the compressive strength of concrete, through the steel plates, enhances significantly both the cracking and ultimate load capacities. For specimens with a shear span-to-effective depth ratio (a/d) of 0.6 and no steel plate strengthening, the ultimate load capacity of CN06M increased by 61.99% compared to CH06M, while the

cracking load increased by 49.53%. Similarly, increases of 44.79% were observed for CNS3M compared to CHS3M.

- Reducing the a/d from 0.6 to 0.3 resulted in an approximate increase in the cracking load of 22.78% for normal-strength vibrated concrete corbels and 40.49% for high-strength vibrated concrete corbels.
- The same reduction in a/d ratio, from 0.6 to 0.3 led to an increase in the ultimate load capacity of 55.9% for the NSC corbels and 95.2% for the HSC corbels.
- Increasing the concrete compressive strength from 30 MPa to 70 MPa increased the maximum failure load and cracking load to 116.63% and 61.99%, respectively.
- Strengthening the corbels with steel plates improved the performance notably. For NSC, the maximum failure load and cracking load increased by 66.91% and 24.40%, respectively, while for HSC, the corresponding increases were 38.26% and 15.18%.

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