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Concrete Corbels: A Narrative Review of Load Transfer Mechanisms, Failure Behaviour, Strut-and-Tie Models, and Design Approaches

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Abstract: Corbels are short projecting cantilevers with concentrated reactions from precast beams and girders that are transferred to supporting columns or walls, which are typically reinforced concrete. They have a low shear span-to-depth (a/d) ratio and are not designed using plane-section beam theory, but rather shear-friction, truss, and strut-and-tie (STM) design. The paper is a narrative review of corbel literature based on three questions: How load is transmitted through a corbel, which failure modes occur and what parameters control them, and how various design methods compare to the experimental results. The review draws on classical shear-friction tests, work on high-strength, fibre-reinforced, FRP-reinforced and strengthened corbels, refined STM and numerical models, and code comparisons. Across the studies, a/d emerges as the dominant parameter, followed by concrete strength and the quantity of main tension and horizontal reinforcement. Softened and compatibility-based STM formulations estimate capacity more accurately than empirical code equations, whereas code STM provisions are conservative and scattered when applied to corbels. Steel fibres have a reliable effect on improving ductility and crack control, but some reports indicate that there is no consistent effect on ultimate load. The critical areas of concern are that there are no strut and node effectiveness factors available for corbels, there is very limited code guidance for fibre-reinforced and FRP-reinforced corbels, and there is no common, quality-controlled test database.

Keywords: concrete corbel; strut-and-tie model; shear friction; shear span-to-depth ratio; failure mode; steel fibres; design codes; narrative review.

Introduction

Corbels, also known as brackets, are short members that extend from the face of a column or wall. They are widely used in precast construction to seat beams, girders and crane runways. A shear span-to-depth ratio below unity and concentrated loads applied close to the support characterise them, so that shear rather than flexure usually controls their strength[1]. The sectional assumptions on which beam-shear equations rely are not valid in such discontinuity regions, and corbels therefore cannot be designed reliably by beam theory[2].

Experimental research on corbels began with the extensive test programme of Kriz and Raths[3] which was adopted directly in design provisions and was later developed by Mattock and co-workers into the shear-friction approach[4][5]. Subsequent work introduced a modified shear-friction theory [6] strut-and-tie formulation[7] high strength and fibre-reinforced concrete[8][9][10][11] ultra-high performance concrete[12] FRP reinforcement[13] and CFRP

strengthening[14].

There are already related reviews. Theoretical models, experimental works and strengthening techniques for corbels were discussed by Shakir[15] and Abbood[16] studied the STM with focus on deep beam. The present paper differs in scope: it connects load-transfer mechanisms with observed failure behaviour, organises the experimental evidence by material and reinforcement type, and assesses design approaches against reported test comparisons. Three research questions guide the review:

- RQ1: Which load-transfer mechanisms govern corbel behaviour?
- RQ2: What are the principal failure modes, and which parameters influence them?
- RQ3: How accurate and how safe are STM-based and code-based design methods relative to experimental results?

The paper is organized as follows: The approach for the review is described in Section 2, load-transfer mechanisms are discussed in Section 3, experimental studies and failure behaviour are reviewed in Section 4, analytical and numerical models are discussed in Section 5, and design approaches are compared in Section 6. The conclusions of the research, the research gaps, and the research limitations are provided in Sections 7 through 9.

Methodology

Review Approach

This is a narrative review. It is not based on a formal PRISMA protocol, and it does not report screening statistics. Literature was selected according to its relevance to the three research questions and its influence on corbel design and research. The procedure is outlined below so that readers can judge the scope of the review.

1. Literature identification

Sources were located through keyword searches in academic databases and search engines [list the databases actually used, for example Scopus, ScienceDirect, Google Scholar], using combinations of the terms corbel, bracket, strut-and-tie, shear strength, shear friction, and failure mode. Foundational studies were added by backward citation tracking from recent papers.

2. Selection criteria

- Included: peer-reviewed journal papers, technical reports and theses presenting corbel tests, analytical or numerical models, or code comparisons; English language; emphasis on studies from 1990 onwards together with influential earlier work.
- Studies excluded: Steel corbels; Non-concrete brackets; Studies that lack methodological details.

3. Organisation of the review

Selected studies were presented in the following clusters according to the research questions: load-transfer mechanisms (Section 3), failure behaviour and influencing parameters (Section 4), analytical and numerical models (Section 5), and design approaches (Section 6). Key findings were summarized in tables. This is a narrative review, so it is not intended to include all corbel studies published, and selection bias may exist as a limitation (Section 8).

Results and Discussion

A. Corbel Behaviour and Load-Transfer Mechanisms

1. Geometry and structural role

A ratio less than 1 is often used to install prefabricated beams or floors at building joints. The load is carried primarily through an inclined compression path from the bearing area to the column, and this is why corbels are considered a disturbed (D) area in the design of struts and ties. Typical reinforcement includes main tension bars at the top, closed or horizontal stirrups covering the corbel depth, and attachment of the main bars at the outer edge.

2. Shear friction

The shear friction concept is based on the hypothesis that a crack occurs at the corbel–column interface, and reinforcement that traverses the crack provides clamping force, which allows for shear to be transferred by the friction and dowel action. Hofbeck tested 38 push-off specimens and reported a conservative value for the strength of the initial crack in concrete. Kriz and Raths conducted a massive corbel test program that paved the way for early design provisions, and the recommendations on quantity and spacing of reinforcement found in ACI 318 were developed from this. Then Mattock and Chen used shear friction for corbels with a/d up to 1.0 subjected to combined vertical and horizontal stresses, and Hermansen and Cowan proposed a modified shear friction theory specifically for brackets.

3. Truss and strut-and-tie action

Corbels are often assumed to be flexural members and are frequently idealised as simple trusses or deep beams. The applied load is carried by an inclined concrete strut from the bearing area to the column and is counterbalanced by a tension tie, which is composed of the main reinforcement and the column. Horizontal stirrups confine the strut and limit diagonal cracking. Strut-and-tie models are widely accepted as a rational basis for designing D-region members, including deep beams and corbels. Refined STM formulations are discussed in Section 5.

4. Flexural action

As a/d grows, flexure becomes more significant and yielding of the main tension reinforcement may control. Fattuhi and Hughes observed a nearly elastic-plastic response in corbels with low main-bar content and relatively large a/d, consistent with a flexure-governed mechanism.

5. Shear friction versus strut action

The two mechanisms are not equivalent. Hwang as cited by Kassem pointed out that the shear-friction hypothesis correlates poorly with the failure actually observed, namely crushing of the diagonal strut. This finding helped motivate STM-based models that represent strut crushing and the role of horizontal reinforcement more directly. In practice, shear friction remains attractive because of its simplicity and its dependence only on the main steel and closed stirrups, whereas STM predictions are strongly affected by concrete strength.

B. Experimental Studies and Failure Behaviour

1. Failure modes

Drawing on the test programme of Kriz and Raths secondary sources divide corbel failures into flexural tension, flexural compression, diagonal splitting, shear friction, bearing crushing, and horizontal tension failure. Other studies describe the main modes as diagonal compression of the strut, shear-compression and diagonal splitting, governed by reinforcement ratio, concrete

strength and loading conditions (Kamal, BFRP study). Corbels containing only main bars tended to fail abruptly, whereas additional shear reinforcement or fibres produced a more gradual response.

2. Influence of main parameters

Table 1 summarises the parameters reported to affect corbel behaviour, with a/d the dominant one. Foster[17] as summarised by Li reported that cracking and bearing capacity fall as a/d rises, and Asaad (MSc thesis) measured capacity reductions of about 17-36% when a/d was increased by 50-200%, accompanied by greater deflection, crack number and crack width.

Concrete strength is also influential. Othman and Aziz tested 14 high-strength corbels with concrete strengths of 40 to 62 MPa; their behaviour resembled that of normal-strength corbels, with capacity increasing with strength and ductile failure retained. Horizontal stirrups were found to be most efficient at the highest strength. Further studies on high-strength, precompressed and short corbels exist[18] Siao[19][20][21] but these were identified from reference lists and should be read in full before being synthesised.

Table 1. Influence of key parameters on corbel behaviour (as reported in the reviewed studies)

Parameter	Reported effect	Source
Shear span-to-depth ratio (a/d)	Most influential parameter; capacity decreases and deflection increases as a/d increases.	Li et al. (2023a); Dang et al. (2024)
Large a/d range (0.5 to 1.5)	Increasing a/d by 50-200% reduced the capacity of reference corbels by about 17-36% and increased deflection and crack width.	Asaad (MSc thesis)
Concrete strength	Capacity increases with strength through the diagonal strut mechanism.	Li et al. (2023a), reporting earlier studies
High-strength concrete (40-62 MPa)	Corbels behaved similarly to normal-strength ones; capacity rose with strength, with ductile failure.	Othman and Aziz (2010)
Main tension reinforcement	Second to a/d in importance for capacity; effect is smaller for GFRP-reinforced corbels.	Li et al. (2023a); Dang et al. (2024)
Horizontal stirrups	Increase capacity; included explicitly in softened STM; effect larger at higher a/d.	Hwang et al. (2000); Han and Huang (2024)
Steel fibres	Mixed: more ductile failure and higher strength in several studies; little effect on ultimate load in one study.	See Section 4.3

3. Fibre-reinforced corbels

Fibre-reinforced corbels have attracted the most attention in recent decades, and the evidence is broadly positive but not uniform. Fattuhi and Hughes showed that steel fibres converted sudden failure into ductile failure in corbels of various a/d. Campione tested plain and fibrous corbels of normal and high strength with different fibre contents and bar arrangements, and showed that fibres and stirrups gave adequate strength and deformation capacity; they also proposed a simplified shear-strength model for fibrous corbels. Abdel Hafez[22] tested 17 high-strength corbels with and without fibres and concluded that fibres, horizontal stirrups, or both enhanced shear strength and ductility and led to a more ductile failure. They also found that the Campione

et al. model predicted the ultimate load of high-strength fibre-reinforced corbels satisfactorily.

Salman[23] tested 10 normal- and high-strength self-compacting corbels with and without fibres. For normal-strength self-compacting concrete, raising the fibre volume from 0 to 0.4% increased the cracking and ultimate loads by about 31.5% and 25.3% respectively, while a further increase to 0.8% added much less. Faleh tested 13 high-strength corbels with different fibre types, fibre contents and amounts of closed stirrups, and concluded that horizontal shear reinforcement can be substituted by steel fibres. In the ultra-high-performance range, Ridha tested 11 corbels with a compressive strength of 150 MPa and reported superior strength and deformation capacity.

The studies do not agree on how large the benefit is. Li tested nine steel-fibre high-strength corbels and found that fibres had little effect on failure mode and ultimate load, although crack resistance improved. The discrepancy probably reflects differences in a/d, fibre type and dosage, concrete strength, and the presence of stirrups, and it represents an important gap for future work (Section 7).

4. FRP-reinforced corbels

Replacing steel with FRP bars is attractive where corrosion is a concern, but test data on corbels remain limited. Dang investigated four GFRP-reinforced corbels and found that a/d and concrete strength affected shear strength and that ACI 440.1R-15 predictions were overly conservative. Kamal (BFRP study) tested double-sided corbels reinforced longitudinally with BFRP bars and reported that shear capacity depended on reinforcement ratio and a/d. Taken together, these studies suggest that FRP-reinforced corbels follow the same strut-controlled mechanisms as steel-reinforced ones, while code provisions for them remain under-calibrated.

5. Strengthening and repair

External strengthening has been studied for existing corbels that must carry higher loads. Erfan tested five full-scale corbels strengthened with CFRP fabrics at a/d = 0.8 and designed to fail in shear; strengthening raised shear capacity by 7% to 13%, and non-linear finite element predictions were conservative. Other works have examined CFRP sheets[24] and STM-based models for CFRP strengthening of corbels[25]. Still, these studies were identified without full access to their results and require detailed review before synthesis.

Table 2. Summary of selected experimental studies on corbels

Study	Specimens and main variables	Main finding
Hofbeck et al. (1969)	38 push-off specimens (shear transfer)	Shear-friction theory conservative for initially cracked concrete.
Mattock and Chen (1976)	Corbels with a/d up to 1.0; combined vertical and horizontal load	Extension of shear-friction design to corbels.
Fattuhi and Hughes (1989)	Steel-fibre corbels, various a/d	Fibres gave more ductile failure.
Hwang et al. (2000)	Database of 178 corbels; softened STM	Better prediction than ACI 318 empirical approach.
Campione et al. (2007)	Plain and fibrous corbels; normal and high strength; fibre %; bar arrangement	Fibres and stirrups ensure adequate strength and deformation; simplified shear model proposed.
Othman and Aziz (2010)	14 HSC corbels, 40-62 MPa; main steel 0.517-1.034%	Capacity rose with strength; ductile failure; stirrups more efficient at 62 MPa.
Erfan et al.	5 full-scale corbels, CFRP fabrics,	7-13% shear gain; NLFEA

Study	Specimens and main variables	Main finding
(2010)	a/d = 0.8	conservative.
Abdel Hafez et al. (2012)	17 HS corbels; fibre content, a/d, stirrups, main steel	Fibres or stirrups improve strength and ductility; Campione model predicted well.
Salman et al. (2014)	10 self-compacting corbels with and without fibres	Fibres 0-0.4% raised cracking and ultimate loads by about 31.5% and 25.3% (NSCC).
Ridha et al. (2017)	11 UHP steel-fibre corbels, 150 MPa	Superior strength and deformation capacity.
Mustafa et al. (2019)	SFRC corbels; STM checked against 146 tests	Code STM more conservative than proposed model.
Faleh et al. (2022)	13 HSC corbels; fibre type, content, closed stirrups	Fibres can replace horizontal stirrups; ACI 318-19 very conservative.
Li et al. (2023a)	9 steel-fibre HSC corbels	Little effect of fibres on failure mode and ultimate load; better crack resistance.
Han and Huang (2024)	8 double corbels with equal STM design load	Actual capacity varied with strength and shear span despite equal design load.
Dang et al. (2024)	4 GFRP-reinforced corbels	a/d dominant; ACI 440.1R-15 overly conservative.

C. Analytical and Numerical Models

1. Strut-and-tie models

Techniques of strut-and-tie and compression-field approach, limit-analysis approach were found to complement each other for structural concrete as shown by Marti[26]. Strut and node effectiveness factors, tie strength and anchorage, and the development of STM were reviewed by Abbood. Several refined models have been proposed for corbels specifically:

- Softened STM satisfies equilibrium, compatibility and cracked-concrete constitutive laws. Checked against 178 corbel tests, it outperformed the empirical ACI 318 approach for all parameters examined (concrete strength, a/d, and horizontal hoop amount).

- Compatibility-based STM incorporates strain compatibility and cracked-concrete constitutive laws in a secant stiffness formulation. It was developed because code STM provisions, written for discontinuity regions in general, give conservative and scattered estimates for corbels.

- Fibre-reinforced STM[27] validated against 146 test results; American and British standard STM predictions were more conservative than the proposed model.

- SSTM for steel-fibre high-strength corbels[28] adds the shear contribution of fibres and was verified against nine new tests and a database of 26 corbels, alongside ACI 318-19, EC2 and CSA A23.3-19 predictions.

- Modified interactive STM[29] based on a biaxial failure criterion for concrete and reported to be more accurate than ACI 318 STM and other models in the literature.

Russo[30] proposed a shear-strength model and design formula for corbels, which later comparisons found accurate for high-strength corbels with closed stirrups, although it omits the

effect of fibres. Lu [31] also addressed the shear strength of reinforced concrete corbels, but their paper was identified only by title and should be examined before use.

2. Shear-friction based models for fibre corbels

For fibre-reinforced corbels, Campione extended a shear-friction type model by adding the fibre contribution through the residual tensile strength of the fibre-reinforced concrete. Such models are easy to apply and have served as a basis for comparison in later studies.

3. Finite element and data-driven models

Non-linear finite element analysis has been applied to reproduce corbel response. Ridha presented a non-linear finite element investigation of high-strength fibre-reinforced corbels, and Erfan compared tests on CFRP-strengthened corbels with finite element predictions, which were conservative. Data-driven approaches have also emerged: Kurtoglu[32] used support vector machines to predict the ultimate shear strength of fibre-reinforced corbels, covering both steel-fibre and glass-fibre concrete. A recent finite element study assessed corbel parameters under different design codes[33]. These models are promising but rely on the quality and size of the available test databases, a recurring limitation (Section 7).

D. Design Approaches and Code Comparison

1. ACI 318 provisions

ACI 318-19 addresses corbels and brackets in Section 16.5, where design combines shear-friction, flexure and direct-tension checks and imposes dimensional limits, including a/d not exceeding 1 and a minimum depth at the outer edge of the bearing area [verify the exact clauses in the code]. Strut-and-tie provisions entered ACI 318 as Appendix A in 2002 and were moved into the main body as Chapter 23 in 2014, and ACI PRC-445.2-21 gives guidance on their application in ACI 318-19[34]. Under ACI 318-11, corbels with a/d below 2 had to be designed by STM, while those with a/d below 1 could be designed by either STM or shear friction.

2. Other codes

Several other codes, among them AS 3600, CSA A23.3, Eurocode 2 and NZS 3101, likewise recommend STM for corbels. The comparisons below indicate that these provisions generally give safe but scattered estimates when checked against corbel test data.

3. Reported comparisons

Table 3. Reported comparisons of design approaches

Study	Methods compared	Main finding
Kassem (2015)	STM provisions of several codes (including ACI, CSA, Eurocode 2, NZS 3101) vs. compatibility-based STM	Code STM estimates conservative and scattered; proposed method more accurate.
Buildings (2022), triangular-truss method study	GB 50010-2010, ACI 318-19, EC2, CSA A23.3-04, softened STM, Russo STM	CSA predictions closest to tests; GB, ACI, and EC2 at essentially the same safety level; softened STM and Russo STM accurate.
Han and Huang (2024)	STM of ACI 318-19; eight double corbels with the same design load but different concrete strength or	Actual capacity changed significantly despite equal design load; safety of STM rose

	shear span	with higher strength or smaller shear span.
Li et al. (2023b)	ACI 318-19, EC2, CSA A23.3-19, and softened STM for SFRHSC corbels	Softened STM with fibre contribution proposed as a rational mechanical model for these corbels.
Faleh et al. (2022)	ACI 318-19 (STM and shear friction) and Russo model for HSC corbels with fibres or closed stirrups	ACI 318-19 gave very conservative values for HSC corbels; Russo model predicted well with stirrups but ignores fibres.
Dang et al. (2024)	ACI 440.1R-15 for GFRP-reinforced corbels	Overly conservative shear strength estimates.
Buildings (2024), FEA study	GB 50010-2010 triangular truss vs. ACI 318-19 STM, 22 numerical specimens at fixed design load	Notes that how parameters change code accuracy at equal design load is under-explored.

Discussion

Three observations follow. First, rational models calibrated on corbel data (softened, compatibility-based and fibre-extended STM) generally achieve higher accuracy than general-purpose code STM provisions, which remain safe but conservative. Second, the conservatism grows for high-strength and fibre-reinforced corbels, because code STM depends on concrete strength but neglects the contribution of closed stirrups or fibres. Third, the safety margin of code STM is not constant: for corbels designed for the same load, greater concrete strength or a smaller shear span gave a higher level of safety[35]. There is a need to have a common database, as it would be difficult to directly compare codes from different studies using different databases and different statistical measures.

Research Gaps and Future Directions

- No common, quality-controlled database of corbel tests exists, so accuracy statistics from different studies cannot be compared directly.
- Strut and node effectiveness factors specific to corbels (bottle-shaped struts, bearing plates, anchorage of main bars) need further calibration.
- The effect of steel fibres on the ultimate load and the failure mode is conflicting and needs to be studied with consistent steel fibre parameters and a/d values.
- Code guidance for FRP-reinforced and fibre-reinforced corbels is limited, and current provisions appear overly conservative for GFRP corbels and for high-strength corbels.
- There are fewer studies on strengthening, and results vary slightly, with modest improvements using CFRP fabrics in some tests (7-13%), hence, further research is called for to optimise CFRP layout and bond behaviour.
- The combined effect of vertical and horizontal loads on STM-based predictions deserves systematic evaluation.
- Data-driven and finite element models need larger, openly documented datasets before they can support design.

Limitations of This Review

This narrative review has limitations. Studies were selected for relevance rather than through an exhaustive protocol, so some relevant work may be missing and selection bias is possible. Several sources were available to the authors only as abstracts or through other papers, and results from such sources are reported in summary form. There are no direct comparisons that can be made between test results of various programmes due to differences in specimen size, materials, and loading arrangements. Conclusions might be reinforced by a systematic review, comprising a fully documented search.

Conclusions

The literature search led to the following conclusions. First, load transfer is best described by a combination of shear-friction and truss or strut-and-tie action, with the dominant mechanism depending on a/d, and the shear-friction hypothesis correlates poorly with the observed crushing of the diagonal strut. Second, a/d is the most influential parameter for capacity and failure mode, followed by concrete strength and reinforcement. Third, steel fibres and horizontal stirrups improve ductility and often strength, although the magnitude of the benefit varies between studies. Fourth, refined STM formulations calibrated on corbel tests predict capacity better than empirical code equations, while general code STM provisions are conservative, particularly for high-strength and fibre-reinforced corbels. Fifth, open issues remain concerning fibres, FRP reinforcement, strengthening and a unified test database. Resolving these would support more economical and consistent corbel design.

References

[1] W. Kassem, "Strength prediction of corbels using strut-and-tie model analysis," *International Journal of Concrete Structures and Materials*, 2015, doi: 10.1007/s40069-015-0102-y.

[2] S.-S. Li, J.-Y. Zheng, J.-H. Zhang, H.-M. Li, G.-Q. Guo, A.-J. Chen, and W. Xie, "Experimental investigation on shear capacity of steel-fiber-reinforced high-strength concrete corbels," *Materials*, vol. 16, no. 8, Art. no. 3055, 2023, doi: 10.3390/ma16083055.

[3] L. B. Kriz and C. H. Raths, "Connections in precast concrete structures: Strength of corbels," *PCI Journal*, Feb. 1965.

[4] J. A. Hofbeck, I. O. Ibrahim, and A. H. Mattock, "Shear transfer in reinforced concrete," *ACI Journal Proceedings*, vol. 66, no. 2, pp. 119–128, 1969.

[5] A. H. Mattock and K. C. Chen, "The behavior of reinforced concrete corbels," *PCI Journal*, Mar. 1976.

[6] B. R. Hermansen and J. Cowan, "Modified shear-friction theory for bracket design," *ACI Journal Proceedings*, vol. 71, no. 2, pp. 55–60, 1974.

[7] S.-J. Hwang, W.-Y. Lu, and H.-J. Lee, "Shear strength prediction for reinforced concrete corbels," *ACI Structural Journal*, vol. 97, no. 4, pp. 543–552, 2000.

[8] N. I. Fattuhi and B. P. Hughes, "Reinforced steel fiber concrete corbels with various shear span-to-depth ratios," *ACI Materials Journal*, vol. 86, no. 6, pp. 590–596, 1989.

[9] G. Campione, L. La Mendola, and M. L. Mangiavillano, "Steel fiber-reinforced concrete corbels: Experimental behavior and shear strength prediction," *ACI Structural Journal*, vol. 104, no. 5, pp. 570–579, 2007.

[10] Z. Othman and D. O. Q. Aziz, “Ultimate shear strength of reinforced high strength concrete corbels subjected to vertical load,” *Al-Rafidain Engineering Journal*, vol. 18, no. 1, pp. 1–12, 2010.

[11] S. K. Faleh, A. H. Chkheiwer, and I. S. Saleh, “Structural behavior of high-strength concrete corbels involving steel fibers or closed stirrups,” *Periodicals of Engineering and Natural Sciences*, vol. 10, no. 1, pp. 239–252, 2022.

[12] M. M. S. Ridha, N. T. H. Al-Shafi'i, and M. M. Hasan, “Ultra-high performance steel fibers concrete corbels: Experimental investigation,” *Case Studies in Construction Materials*, vol. 7, pp. 180–190, 2017, doi: 10.1016/j.cscm.2017.07.004.

[13] H. V. Dang, S. D. Nguyen, A. V. Le, and D. P. Nguyen, “Experimental study of the behavior of GFRP reinforced concrete corbels,” *Journal of Materials and Engineering Structures*, vol. 11, no. 4, pp. 361–368, 2024.

[14] A. M. Erfan, G. T. Abdel-Rahman, M. K. Nassif, and Y. H. Hammad, “Behaviour of reinforced concrete corbels strengthened with CFRP fabrics,” *Journal of Al-Azhar University Engineering Sector*, 2010.

[15] Q. M. Shakir, “Analysis, behavior, strengthening and repairing of reinforced concrete corbels: Comprehensive review,” *Journal of Materials and Engineering Structures*, vol. 10, no. 2, pp. 157–184, 2023.

[16] I. S. Abbood, “Strut-and-tie model and its applications in reinforced concrete deep beams: A comprehensive review,” *Case Studies in Construction Materials*, vol. 19, Art. no. e02643, 2023.

[17] S. J. Foster, R. E. Powell, and H. S. Selim, “Performance of high-strength concrete corbels,” *ACI Structural Journal*, vol. 93, no. 5, pp. 555–563, 1996.

[18] P. R. Chakrabarti, D. J. Farahi, and S. I. Kashou, “Reinforced and precompressed concrete corbels: An experimental study,” *ACI Structural Journal*, vol. 86, no. 4, pp. 132–142, 1989.

[19] W. B. Siao, “Shear strength of short reinforced concrete walls, corbels, and deep beams,” *ACI Structural Journal*, vol. 91, no. 2, pp. 123–132, 1994.

[20] Y. Yong and P. Balaguru, “Behavior of reinforced high-strength-concrete corbels,” *Journal of Structural Engineering*, vol. 120, no. 4, pp. 1182–1201, 1994, doi: 10.1061/(ASCE)0733-9445(1994)120:4(1182).

[21] M. Bourget, Y. Delmas, and F. Toutlemonde, “Experimental study of the behaviour of reinforced high-strength concrete short corbels,” *Materials and Structures*, vol. 34, no. 3, pp. 155–162, 2001, doi: 10.1007/BF02480506.

[22] A. M. Abdel Hafez, M. M. Ahmed, and H. Diab, “Shear behaviour of high strength fiber reinforced concrete corbels,” *Journal of Engineering Sciences, Assiut University*, vol. 40, no. 4, pp. 969–987, 2012.

[23] M. M. Salman, I. Al-Shaarbaf, and J. M. Aliewi, “Experimental study on the behavior of normal and high strength self-compacting reinforced concrete corbels,” *Journal of Engineering and Development*, vol. 18, no. 6, pp. 17–35, 2014.

[24] Y. S. S. Al-Kamaki, G. B. Hassan, and G. Alsofi, “Experimental study of the behaviour of RC corbels strengthened with CFRP sheets,” *Case Studies in Construction Materials*, vol. 9, Art. no. e00181, 2018.

[25] A. Kheyroddin, S. Raygan, and M. Kioumarsi, “Strut and tie model for CFRP strengthened reinforced concrete corbels,” *Engineering Structures*, vol. 304, Art. no. 117609, 2024.

[26] P. Marti, “How to treat shear in structural concrete,” *ACI Structural Journal*, vol. 96,

no. 3, pp. 408–414, 1999.

[27] T. S. Mustafa, F. B. A. Beshara, A. A. Mahmoud, and M. M. A. Khalil, "An improved strut-and-tie model to predict the ultimate strength of steel fiber-reinforced concrete corbels," *Materials and Structures*, vol. 52, no. 3, 2019.

[28] S.-S. Li, J.-Y. Zheng, F.-J. Zhang, *et al*., "Prediction of shear strength for steel-fiber high-strength concrete corbels with the softened strut-and-tie model," *Buildings*, 2023.

[29] P. Chetchotisak, P. Rulak, and J. Teerawong, "Modified interactive strut-and-tie model for shear strength prediction of RC corbels," *Engineering and Applied Science Research*, 2019, doi: 10.14456/easr.2019.3.

[30] G. Russo, R. Venir, M. Pauletta, and G. Somma, "Reinforced concrete corbels: Shear strength model and design formula," *ACI Materials Journal*, vol. 103, no. 1, pp. 3–10, 2006.

[31] W.-Y. Lu, I.-J. Lin, and S.-J. Hwang, "Shear strength of reinforced concrete corbels," *Magazine of Concrete Research*, vol. 61, pp. 807–813, 2009.

[32] A. E. Kurtoglu, "Predicting the shear strength of fiber reinforced concrete corbels via support vector machines," *Cumhuriyet Science Journal*, vol. 39, no. 2, pp. 496–514, 2018, doi: 10.17776/csj.434263.

[33] "Finite element analysis of the shear performance of reinforced concrete corbels under different design codes," *Buildings*, vol. 14, no. 10, Art. no. 3100, 2024.

[34] ACI-ASCE Committee 445, *Strut-and-Tie Method Guidelines for ACI 318-19*, ACI PRC-445.2-21. Farmington Hills, MI, USA: American Concrete Institute, 2021.

[35] B. Han and Y. Huang, "Shear test on concrete corbels: ACI 318-19 formulas evaluation," *ACI Structural Journal*, vol. 121, no. 3, pp. 3–14, 2024, doi: 10.14359/51740455.