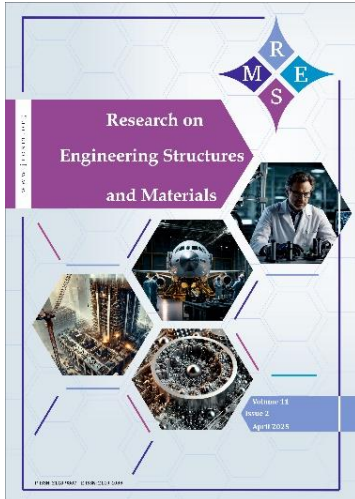




Research on Engineering Structures & Materials

www.jresm.org



Shear capacity of RC corbels: Systematic review, code models, and SHAP-based machine learning

Maher K. Abbas, Ammar Yasir Ali

Online Publication Date: 10 September 2026

URL: <http://www.jresm.org/archive/resm2026-1833st0707rv.html>

DOI: <http://dx.doi.org/10.17515/resm2026-1833st0707rv>

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article

Abbas M K, Ali A Y. Shear capacity of RC corbels: Systematic review, code models, and SHAP-based machine learning. *Res. Eng. Struct. Mater.*, 2026; 12(5): 4051-4102.

Disclaimer

All the opinions and statements expressed in the papers are on the responsibility of author(s) and are not to be regarded as those of the journal of Research on Engineering Structures and Materials (RESM) organization or related parties. The publishers make no warranty, explicit or implied, or make any representation with respect to the contents of any article will be complete or accurate or up to date. The accuracy of any instructions, equations, or other information should be independently verified. The publisher and related parties shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with use of the information given in the journal or related means.



Published articles are freely available to users under the terms of Creative Commons Attribution - NonCommercial 4.0 International Public License, as currently displayed at [here](#) (the "CC BY - NC").

Shear capacity of RC corbels: Systematic review, code models, and SHAP-based machine learning

Maher K. Abbas ^{*,1,2,a}, Ammar Yasir Ali ^{1,b}

¹Department of Civil Engineering, College of Engineering, University of Babylon, Babylon, Iraq

²Civil Engineering Department, College of Engineering, Al-Qasim Green University, Babylon, Iraq

Article Info

Article History:

Received 07 July 2026

Accepted 31 Aug 2026

Keywords:

RC corbels;
Systematic review;
Shear capacity;
Design codes;
XGBoost;
SHAP analysis

Abstract

This review presents a systematic review and SHAP-based interpretation of machine-learning (ML) predictions for reinforced concrete corbels (RCCs). A structured PRISMA-guided review was conducted using Scopus and Web of Science records, supplemented by reference checking. After duplicate removal and screening, 121 studies were retained for qualitative synthesis. The review discusses the effects of key parameters, including concrete compressive strength, span-to-depth ratio, corbel geometry, reinforcement, and loading history. Strengthening and repair studies were reviewed as a separate practical branch of the literature, while analytical and code-based models, including shear-friction, strut-and-tie, and triangular-truss approaches, were examined to clarify their assumptions and limitations. In the ML component, an XGBoost model was trained using 330 compatible vertical-load specimens with 13 min-max normalized input variables to predict the normalized experimental shear capacity, using an 80:20 training-testing split and a fixed random seed of 42. The model achieved R² values of 0.9973 and 0.9090 and RMSE values of 0.0066 and 0.0388 for the training and testing sets, respectively; the gap between them indicates mild overfitting, so the model is used for interpretation rather than as a design equation. SHAP analysis was then applied to explain the influence of the main input variables. The results demonstrate that member geometry, a/d ratio, and concrete strength dominate the prediction trend, while reinforcement-related variables provide secondary but still meaningful contributions within the database range. The findings highlight the value of combining systematic review, code-model assessment, and explainable ML for understanding RCCs behavior.

© 2026 MIM Research Group. All rights reserved.

1. Introduction

RC corbels (RCCs) are short cantilever-like members that project from columns or walls to support beams, girders, crane loads, and other concentrated actions [1-3], especially in precast concrete construction [4]. Because of their short shear span and discontinuity-region behavior, their response is usually governed by nonlinear stress transfer rather than ordinary beam action. The applied load is mainly resisted through a diagonal compression strut, while the main tensile reinforcement, secondary reinforcement, and nodal zones complete the internal load path. For this reason, corbels are commonly treated as disturbed regions where conventional sectional analysis is not sufficient. Previous experimental studies have shown that corbels with small shear span-to-effective depth ratios are particularly prone to shear-dominated failure, concrete crushing, diagonal splitting, anchorage distress, or yielding of the main reinforcement [5-7].

The shear load capacity of RCCs is affected by several geometric, material, and reinforcement-related parameters. These include concrete compressive strength, shear span-to-depth ratio,

*Corresponding author: maherkheder@wrec.uoqasim.edu.iq

^aorcid.org/0000-0003-4954-7587; ^borcid.org/0009-0009-6698-1327

DOI: <http://dx.doi.org/10.17515/resm2026-1833st0707rv>

Res. Eng. Struct. Mat. Vol. 12 Iss. 5 (2026) 4051-4102

corbel width, effective depth, column width, longitudinal reinforcement ratio, transverse reinforcement, anchorage detailing [8], and the yield strength of reinforcement. Earlier studies have generally reported that smaller a/d ratios, higher concrete strength, and improved reinforcement detailing can increase the ultimate load capacity and improve ductility. However, the influence of these variables is strongly interactive, which makes corbel behavior difficult to represent using simple empirical equations. This complexity is one of the main reasons why design provisions continue to rely on simplified approaches such as the shear-friction method and the strut-and-tie method.

International design codes, including ACI 318-25 [9], EN 1992-1-1 [10], and GB 50010-2010 [11], provide practical methods for corbel design based on different mechanical assumptions. The shear-friction method is commonly used for short corbels, while the strut-and-tie method idealizes the member as a truss composed of concrete compression struts, steel tension ties, and nodal regions. Although these methods are useful for design practice, recent comparisons with experimental databases have shown that code-based predictions may be conservative, scattered, or inconsistent, especially when the tested specimens include variations in geometry and reinforcement detailing [9-12].

Despite the large number of studies on RCCs, the available literature remains dispersed across different specimen types, materials, reinforcement layouts, loading conditions, and prediction approaches. Some studies deal with conventional RCCs, while others focus on fibre-reinforced concrete, high-strength concrete, strengthened corbels, or special loading cases. This variation makes it difficult to draw clear conclusions without a transparent and reproducible review process. In this study, papers addressing specimens subjected to direct horizontal force are excluded so that the review remains focused on corbels governed mainly by vertical loading and shear load capacity. This boundary is important because horizontal-force interaction introduces a different mechanical problem involving additional tie force, N/V effects, and moment transfer at the corbel-column interface.

The practical importance of this member class is closely linked to precast concrete construction, and the specific challenges of precast systems influence both the design and the analysis of RCCs. In a precast frame, the corbel is not an isolated cantilever but the physical interface through which a beam or girder is seated on a column, so its performance is coupled to the connection detailing around it. Lacerda et al. [1] showed that the condition of the interface between corbel and beam, including the vertical grouting of the joint, changes the measured behavior of beam-to-column connections, which means that the boundary condition assumed in a laboratory corbel test may not reproduce the boundary condition of the same corbel in an assembled frame. Similarly, de Lima Araujo et al. [4] required a dedicated computational and analytical treatment for two-step corbels used in precast systems, because the stepped geometry adopted for erection and seating purposes redistributes the internal load path relative to a plain corbel. Three consequences follow for design and analysis. First, precast corbels must accommodate erection tolerances, bearing pads, and seating eccentricities, so the effective shear span is not always known with the precision assumed in a strut-and-tie idealization. Second, the corbel region carries not only gravity actions but also the forces generated by volume change, restraint, and, in seismic regions, joint rotation, as reflected in studies of precast beam-slab-column joints and of precast corbel and nib connections under cyclic loading [99,100]. Third, because precast members are produced under controlled conditions but assembled on site, the governing uncertainty often shifts from material strength to detailing and workmanship at the joint. These considerations explain why the present review keeps strengthened, repaired, and non-conventional corbels as a separate branch of the evidence, and why the machine-learning dataset defined later is restricted to specimens tested under a well-controlled vertical-load configuration.

Recently, artificial neural networks have been increasingly used to predict the shear strength of reinforced concrete members because they can capture nonlinear relationships among several input parameters. For RCCs, Abbas and Ali developed a backpropagation neural network model using 330 experimentally tested specimens and reported that the best architecture, 13-10-9-1, achieved a Pearson correlation coefficient of 0.990. Their results showed better agreement with

experimental data than several code-based methods, whose correlation coefficients ranged from 0.901 to 0.927. However, ANN models remain dependent on the quality and range of the experimental database used for training and validation. Therefore, their use should be supported by a careful review of the available experimental evidence and clear identification of the model's applicability limits [13].

Accordingly, this study aims to present a systematic review and explainable ML interpretation of the shear capacity of RCCs subjected mainly to vertical loading. To achieve this, a structured PRISMA-guided review was conducted to identify, classify, and synthesize the available experimental, analytical, numerical, code-based, strengthening, repair, and ML-related studies on RCCs. The review focuses on the main parameters affecting shear behavior. In addition, the study reviews strengthening and repair approaches for deficient or damaged RCCs. The study also evaluates analytical and code-based models, including shear-friction, strut-and-tie, and triangular-truss approaches, to clarify their assumptions, applicability limits, and prediction challenges.

In addition to the systematic review, this study develops an XGBoost model to support the interpretation of the experimental database. SHAP analysis is then employed to quantify the contribution of each variable to the predicted shear capacity and to connect the ML results with the physical behavior of RCCs. Therefore, the main contribution of this study lies in combining a systematic literature review, code-based assessment, strengthening and repair synthesis, and SHAP-based explainable ML interpretation within a unified framework for understanding RCCs shear behavior.

2. Systematic Review Methodology

This study used a PRISMA-guided systematic review procedure to identify, screen, classify, and synthesize previous research on RCCs. The procedure was designed for two connected purposes. First, it provided a transparent route for building the qualitative review corpus. Second, it defined a traceable evidence base from which specimen-level data could be extracted for the ML component. The PRISMA 2020 statement was used as a reporting guide for the identification, screening, eligibility, and inclusion stages [14], as summarized in Fig. 1.

The review mainly addresses RCCs governed by vertical-load and shear-capacity behavior. Studies dealing with special materials, non-conventional reinforcement, strengthening, repair, or retrofitting were retained when they provided useful information on RCCs behavior, but they were classified separately during synthesis. This distinction is important because these studies may involve additional variables, such as fibre content, FRP layout, repair material, bond condition, or anchorage details. By contrast, the ML dataset used later in this paper was restricted to compatible specimens tested under vertical loading only. Specimens involving direct horizontal forces, combined vertical-horizontal loading, strengthening or repair, and special materials were not used for the ML training and SHAP interpretation dataset.

2.1 Review Scope and Research Questions

The review scope covered RCCs, concrete brackets, and short cantilever-type corbels tested or analyzed in relation to shear strength, ultimate load, failure behavior, design prediction, or rehabilitation performance. Direct horizontal-force and combined-load studies were treated as outside the main vertical-load corpus because they introduce a different mechanical problem involving N/V interaction, additional tie demand, and moment transfer at the corbel-column interface. However, studies on strengthened, repaired, fibre-reinforced, recycled aggregate, UHPC, SCC, GFRP/CFRP-reinforced, and other non-conventional corbels were included when they helped explain corbel behavior or practical performance.

The review was directed by the following research questions:

- What geometric, material, and reinforcement parameters have been most frequently investigated in previous studies on RCCs?
- How do these parameters influence the shear load capacity and failure behavior of RCCs?
- How accurately do current design methods estimate the shear strength of RCCs?

- Which studies provide specimen-level data suitable for ML-based interpretation of vertical-load corbel shear capacity?

2.2 Search Strategy

A structured database search was conducted using Web of Science Core Collection and Scopus. These databases were selected because they provide broad coverage of peer-reviewed engineering literature and allow advanced searching by title, abstract, and keywords. The Web of Science search used the Topic field, while the Scopus search used TITLE-ABS-KEY, which is the closest equivalent field in Scopus. The database search strategy is summarized in Table 1.

The search was carried out in two stages. First, a broad search was performed using terms related to RCCs and shear/load capacity. Second, exclusion terms were added to reduce records explicitly governed by direct horizontal-force interaction. The official indexed search produced 69 records from Web of Science and 124 records from Scopus, giving 193 records before duplicate removal. These numbers represent the auditable WoS/Scopus corpus used in the PRISMA process.

Table 1. Database search strategy

Database	Search date	Search field	Core search terms	Horizontal-force NOT terms	Records before / after NOT terms
Web of Science Core Collection	14 May 2026	Topic	("reinforced concrete corbel" OR "RC corbel" OR "concrete corbel" OR "reinforced concrete bracket" OR "short cantilever*") AND ("shear strength" OR "shear capacity" OR "load capacity" OR "ultimate load" OR "failure load")	("horizontal force" OR "horizontal load" OR "horizontal-to-vertical" OR "N/V" OR "axial force" OR "combined vertical and horizontal")	70 / 69
Scopus	14 May 2026	TITLE-ABS-KEY	("reinforced concrete corbel" OR "RC corbel" OR "concrete corbel" OR "reinforced concrete bracket" OR "short cantilever*") AND ("shear strength" OR "shear capacity" OR "load capacity" OR "ultimate load" OR "failure load")	("horizontal force" OR "horizontal load" OR "horizontal-to-vertical" OR "N/V" OR "axial force" OR "combined vertical and horizontal")	134 / 124

Note: both searches covered 1960-2026 and were limited to English articles or review articles. Retrieved WoS records were from 2006-2026, while retrieved Scopus records were from 1974-2026.

The Scopus and Web of Science searches were treated as the main indexed search, but they did not cover all relevant RCCs literature. Several useful studies were found through Google Scholar, backward reference checking, and older reference lists, particularly works indexed under alternative terms such as "bracket", "short cantilever", or "D-region member". These supplementary sources were used where they supported the technical discussion, but they were not automatically counted as part of the main indexed PRISMA corpus unless they met the same scope criteria.

2.3 Eligibility Criteria

The eligibility criteria were defined before screening so that the selected studies remained consistent with the purpose of the review. As shown in Table 2, the main inclusion condition was that the study should address RCCs, concrete brackets, or short cantilever-type members in relation to shear strength, load capacity, ultimate load, failure behavior, design modelling, or strengthening/repair performance. Studies were not excluded simply because they used special concrete, non-conventional reinforcement, or strengthening systems. Instead, these records were retained and classified separately. Papers were excluded or treated only as boundary references when they clearly fell outside the structural scope, such as non-structural corbels, unrelated members, or specimens dominated by direct horizontal-force interaction [15]-[17].

Table 2. Inclusion and treatment criteria

Category	Inclusion criteria	Exclusion criteria / treatment
Structural element	RCCs, concrete brackets, and short cantilever-type corbels	Steel, timber, masonry, architectural, or non-structural corbels were excluded.
Loading condition	Studies relevant to vertical-load, shear-capacity, cyclic/repeated-load, or practical corbel behavior	Direct horizontal-force or combined vertical-horizontal interaction studies were not retained in the main vertical-load corpus.
Main response	Ultimate shear load, failure load, shear strength, load capacity, cracking, stiffness, or failure mode	Studies unrelated to structural load capacity or corbel behavior were excluded.
Study type	Experimental, analytical, numerical, code-comparison, review, or ML studies related to RCCs	Papers without technical relevance to RCCs behavior were excluded.
Material type	Conventional concrete, high-strength concrete, UHPC, SCC, recycled aggregate concrete, geopolymers concrete, fibre-reinforced concrete, and other non-conventional materials	Material type was recorded and classified; special materials were retained for qualitative synthesis but not used in the ML dataset.
Strengthening condition	Original, strengthened, repaired, retrofitted, or externally bonded RCCs	Strengthening and repair studies were retained for qualitative synthesis and discussed separately; they were not used in the ML dataset.
Loading history	Monotonic, repeated, cyclic, or fatigue-related corbel studies	Loading history was recorded separately; only compatible vertical-load specimens were considered for ML extraction.
Data completeness	Studies with information useful for qualitative synthesis, quantitative extraction, or ML-related discussion	Incomplete specimen-level data did not prevent qualitative use, but limited ML suitability.
Language	English-language publications	Non-English publications were not included.
Publication type	Journal articles, review articles, conference papers, theses, standards, and technical reports where relevant	Codes, textbooks, standards, and methodological references were used as supporting sources and were not counted as main included studies.

2.4 Screening and Study Selection

The screening process included identification, duplicate removal, title/abstract/keyword screening, a second careful screening of borderline records, and full-text eligibility assessment. The official indexed search produced 193 records, including 69 records from Web of Science and 124 records from Scopus, as reported in Table 3. After merging the two datasets, 58 duplicate records were removed using exact DOI matching where available and normalized-title matching where DOI information was missing. This left 135 unique indexed records for screening.

During screening, strengthening, repair, retrofitting, and special-material corbel studies were retained when they addressed RCCs behavior. The main scope boundary was horizontal-force or combined vertical-horizontal loading behavior, because these cases introduce a different mechanical problem involving N/V interaction, additional tie demand, and moment transfer at the corbel-column interface. In the first screening stage, 11 indexed records were flagged as horizontal-force or combined-load records and were not retained in the main vertical-load/shear-capacity corpus. After a second careful screening of the indexed records, three additional indexed records

were also found to fall outside the main vertical-load scope. Accordingly, a total of 14 indexed records were not retained, leaving 121 studies for the final systematic corpus used in the qualitative synthesis, as summarized in Fig. 1 and Table 3.

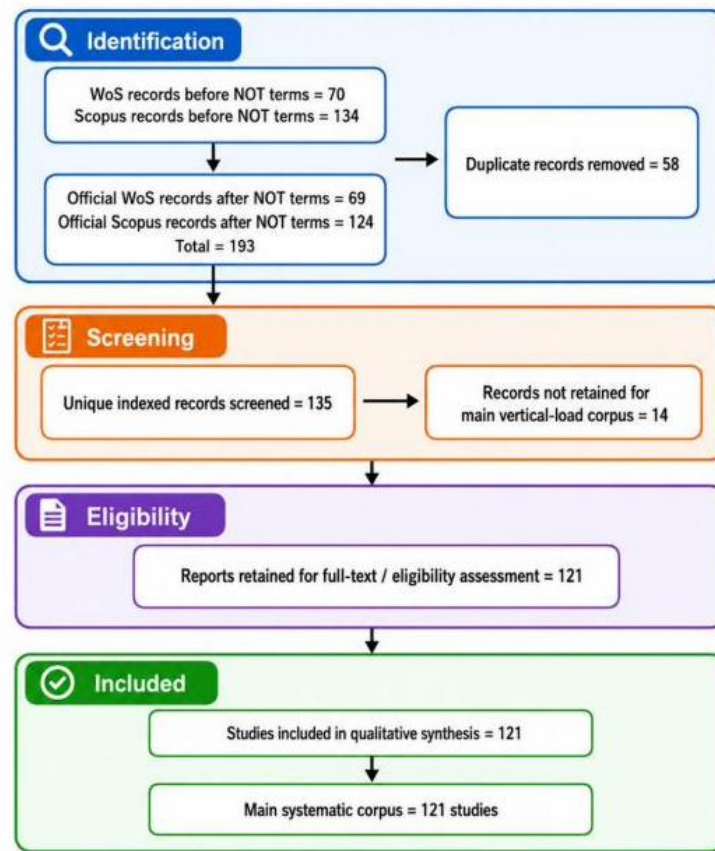


Fig. 1. PRISMA flow diagram of the study selection process

Table 3. Screening summary for Web of Science and Scopus

Screening stage	Number of records
Web of Science records before NOT terms	70
Web of Science official records after NOT terms	69
Scopus records before NOT terms	134
Scopus official records after NOT terms	124
Total official indexed records before duplicate removal	193
Duplicate records removed	58
Unique indexed records after duplicate removal	135
Indexed records flagged as horizontal-force or combined-load scope during first screening	11
Additional indexed horizontal-force or combined-load records flagged after second careful screening	3
Total indexed records not retained for the main vertical-load/shear-capacity corpus	14
Main eligible studies after screening	121
Reports retained for full-text/eligibility assessment	121
Reports excluded after full-text assessment	0
Studies included in qualitative synthesis	121

The screening flags were used to clarify how borderline records were treated rather than to remove all non-conventional corbel studies. This is shown in Table 4. Strengthening, repair, and special-material studies were retained because they provide useful behavioral evidence, but the results were interpreted separately from the unstrengthened vertical-load specimens used for ML analysis.

Table 4. Classification and treatment during screening

Screening category	Count / status	Treatment
Horizontal-force or combined-load scope within indexed records during first screening	11	Not retained in the main vertical-load/shear-capacity corpus.
Additional indexed horizontal-force or combined-load records identified during second careful screening	3	Not retained in the main vertical-load/shear-capacity corpus.
Total indexed records not retained for the main vertical-load/shear-capacity corpus	14	Removed from the main systematic corpus because their behavior was governed by horizontal-force or combined-load interaction.
Strengthening, repair, or retrofitting corbel studies	Retained	Included in qualitative synthesis and discussed as a separate subgroup.
Special concrete, special materials, or non-conventional reinforcement	Retained	Included in qualitative synthesis and classified by material or reinforcement type.
Main eligible systematic corpus	121	Used for qualitative synthesis; supporting references are cited separately when needed.

2.5 Data Extraction

For each of the 121 studies in the main systematic corpus, bibliographic, experimental, numerical, and modelling information was organized according to the data extraction form presented in Table 5. The extracted information included author name, publication year, journal, study type, number of specimens, concrete type, loading setup, investigated variables, failure modes, and main findings. When a cited source was used only for background, code explanation, methodology, or secondary context, it was not counted as part of the main systematic corpus.

For studies suitable for quantitative analysis or ML interpretation, specimen-level data were also examined. These data included concrete compressive strength, shear span, effective depth, corbel width, column width, total depth, shear span-to-depth ratio, longitudinal reinforcement ratio, transverse reinforcement ratio, steel yield strength, and experimental ultimate shear load. As shown in Table 5, each study was checked for ML suitability based on the availability of the required input and output variables and the compatibility of the test conditions.

The ML-related data structure was aligned with the earlier data-driven model by Abbas and Ali (2025) [13], who used 330 experimentally tested RCC specimens. In the present work, this boundary was kept clear: the ML dataset included only specimens under vertical loading and did not include direct horizontal-force specimens, strengthened or repaired corbels, or specimens made with special materials. Thus, the ML dataset represents a controlled subset of the broader systematic review corpus rather than the full set of studies discussed qualitatively.

Table 5. Data extraction form

Data group	Extracted variables
Bibliographic information	Author(s), year, title, journal, DOI
Study information	Study type, number of specimens, experimental/numerical/analytical approach
Specimen type	RC corbel, concrete bracket, short cantilever-type corbel
Loading condition	Vertical monotonic loading, repeated/cyclic loading, loading setup, support condition
Geometry	Shear span, effective depth, total depth, width, column width, a/d ratio
Concrete properties	Concrete compressive strength and concrete type
Reinforcement details	Longitudinal reinforcement ratio, vertical reinforcement ratio, horizontal reinforcement ratio, bar yield strengths
Response variables	Experimental ultimate shear load, failure load, failure mode, crack pattern
Qualitative classification	Original, strengthened/repared, special material, cyclic/repeated, numerical, analytical, code-based, or ML study
ML suitability	Complete data, missing data, compatible/not compatible with the vertical-load ML dataset
ML exclusion notes	Horizontal force, strengthening/repair, special materials, repeated/cyclic loading, or missing specimen-level data

2.6 Data Adequacy and Quality Assessment

The quality assessment was handled as a data-adequacy check rather than as a rigid numerical score. This approach was more suitable for the present review because the included literature covers different types of evidence, including experimental studies, numerical simulations, analytical models, review papers, design-code comparisons, and strengthening/repair studies. A single score would not fairly describe the usefulness of these different sources.

Table 6. Final data-use assessment outcome

Assessment outcome	Result / treatment
Reports retained for full-text/eligibility assessment	121
Reports excluded after full-text assessment	0
Studies included in qualitative synthesis	121
Studies considered for specimen-level quantitative extraction	Controlled subset based on data completeness and compatibility
Studies considered for ML interpretation	Only vertical-load specimens without horizontal force, strengthening/repair, or special materials

The outcomes of the data adequacy assessment are summarized in Table 6. At the screening level, each record was checked for relevance to RCCs behavior and for consistency with the vertical-load scope. At the full-text level, the main concern was whether the study provided enough information for its intended use. For qualitative synthesis, a study was retained when it offered useful behavioral, analytical, numerical, design, or rehabilitation insight. For specimen-level quantitative extraction and ML-related use, the requirements were stricter: the study had to report the main geometry, concrete strength, reinforcement information, loading arrangement, and ultimate load.

Studies with incomplete specimen-level data were still useful for qualitative discussion but were not treated as equally suitable for ML extraction.

2.7 Data Synthesis

The selected studies were synthesized in two complementary ways. First, a qualitative synthesis was conducted using the 121-study main corpus to discuss the development of RCCs research, the main investigated parameters, common failure mechanisms, strengthening and repair strategies, and the limitations of existing design and prediction approaches [18]. Second, specimen-level extraction was considered only for studies that provided sufficient data and compatible test conditions for quantitative or ML-related analysis.

For the ML component, the systematic review was used to define a transparent candidate literature pool and to justify the data-selection boundaries. The ML analysis should therefore be understood as a systematic-review-supported modelling exercise, not as an independent black-box prediction study. The XGBoost and SHAP analysis used later in this paper is limited to the compatible vertical-load subset and is intended mainly to interpret parameter influence rather than to replace mechanics-based design provisions.

2.8 Methodological Recommendations for Systematic Reviews

The procedure applied above also exposed several practical difficulties that are typical of systematic reviews in structural and civil engineering, and the way they were handled here can be generalized. Six recommendations follow directly from the present experience and are offered for reviews of comparable structural topics.

First, a single indexed database is not sufficient. As reported in Section 3.2, 66 of the 135 unique records were indexed only in Scopus and 11 only in Web of Science, so a review based on either database alone would have missed a substantial share of the evidence. At least two complementary indexes should therefore be searched, and the overlap should be reported rather than assumed. Second, the search string must accommodate the synonyms that structural engineering has accumulated over time. The same member appears in the literature as a corbel, a bracket, a short cantilever, and a D-region member, and older work is frequently indexed only under the alternative terms; truncated wildcards and explicit synonym sets are therefore necessary rather than optional. Third, indexed searching should be complemented by backward reference checking. Several foundational corbel studies from the 1960s and 1970s were retrievable in the present review only through the reference lists of later papers, because their indexing metadata predates modern abstracting practice. Fourth, the scope boundary should be defined mechanically, not merely thematically. Here the boundary was the presence of direct horizontal-force or combined vertical-horizontal interaction, which changes the internal force system rather than simply adding a variable; expressing the boundary through explicit NOT terms and reporting the record counts before and after their application, as in Table 1, makes the decision auditable. Fifth, when a review supports quantitative or data-driven synthesis, the qualitative corpus and modelling dataset should remain separate, with exclusion reasons recorded at the specimen level; this preserves the breadth of the narrative synthesis while avoiding incompatible test conditions in the modelling dataset. Applying these six practices makes the search reproducible, keeps the treatment of borderline records transparent, and allows a later reader to reconstruct why a given study was retained, reclassified, or set aside.

3. Descriptive Analysis of the Selected Literature

The descriptive analysis provides an overview of the RCCs research landscape before the technical synthesis. The analysis uses the final screening structure reported in Section 2 and the descriptive source data prepared from the indexed search records. It is important to note that Figs 2-4 are descriptive figures. Fig. 2 presents the publication activity of the official indexed search records, Fig. 3 shows the database coverage of the 135 unique indexed records after duplicate removal, and Fig. 4 summarizes the main research/source-category tags identified during screening. These figures help explain publication activity, database coverage, and research/source categories, but

they should not be read as direct PRISMA inclusion counts. The final systematic corpus is the 121-study corpus reported in Fig. 1 and Table 3.

3.1 Publication Trend

The publication trend is presented in Fig. 2. Fig. 2(a) shows the annual distribution of the official Web of Science records, while Fig. 2(b) shows the Scopus records grouped by publication interval. The trend confirms that RCCs research has continued over several decades, with more visible activity in recent years. This increase can be linked to the growing interest in precast concrete systems, D-region design, strut-and-tie modelling, special concrete materials, numerical simulation, and data-driven prediction methods [19]-[22].

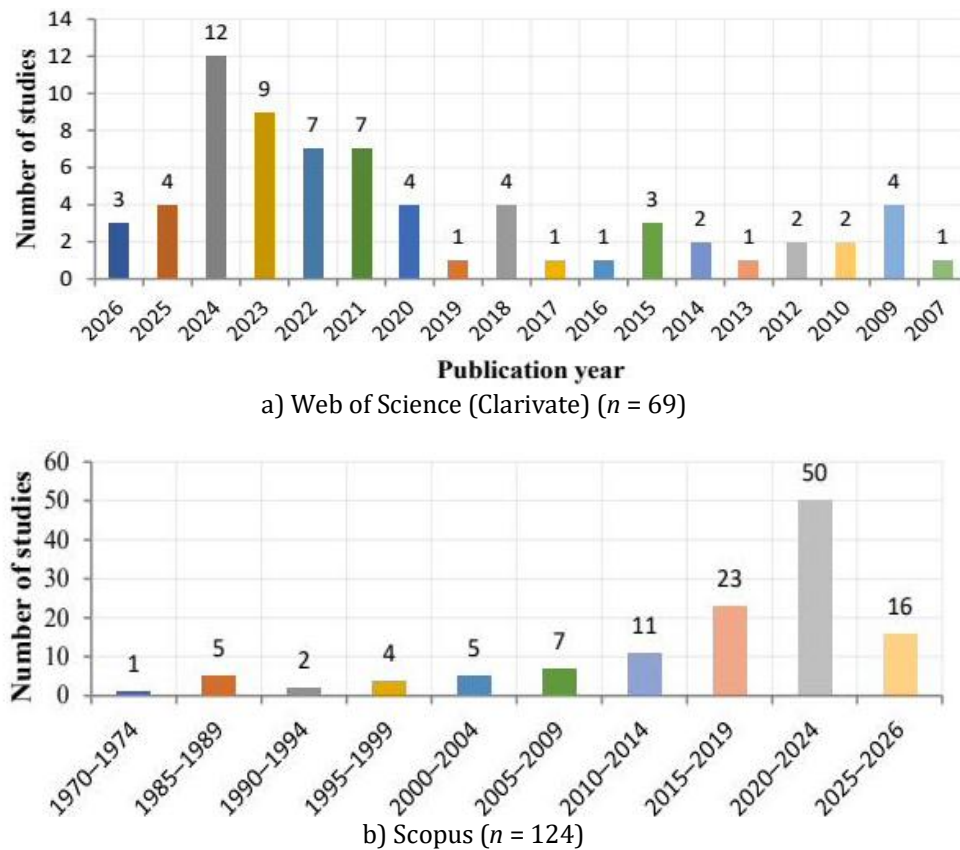


Fig. 2. Publication trend of the official indexed search records

The shape of this trend has consequences for design practice, and not only for bibliometrics. Two features are relevant. The first is the concentration of output in the most recent intervals: in the Scopus record set, 50 of the 124 records fall in the 2020-2024 interval and a further 16 in 2025-2026, so roughly half of the retrieved corbel literature has appeared within the last six years. Design provisions for corbels, by contrast, retain the essential structure they were given decades ago, with the shear-friction expressions still traceable to Kriz and Rathes [15] and Mattock et al. [17]. A widening gap therefore exists between the evidence base and the codified rules, and it is this gap, rather than any deficiency in the rules themselves, that explains the scatter reported when code predictions are compared with modern experimental databases. The second feature is a change in the composition of the output. As shown in Section 3.3, computational modelling and AI-related sources, composites and advanced materials, and concrete and construction materials together account for a substantial share of the recent records, whereas the earlier literature was dominated by monotonic tests on conventional normal-strength specimens. Practically, this means that the specimens now entering the literature increasingly involve high-strength and fibre-reinforced concrete, recycled aggregate, GFRP and CFRP reinforcement, and strengthened or repaired configurations, that is, precisely the cases for which the empirical calibration underlying the current provisions was not established. Three implications follow for future design practice. Code committees will need to draw on databases that are wider than those originally used for calibration,

particularly with respect to concrete strength and reinforcement type. The growing volume of numerical and data-driven work offers a route to parametric coverage that testing alone cannot provide, provided the models are interpretable and their applicability ranges are stated. Finally, because much of the recent growth is driven by non-conventional materials, future provisions are likely to require explicit applicability limits rather than a single expression applied uniformly across all corbel types.

3.2 Database Coverage

The database-coverage distribution of the 135 unique indexed records after duplicate removal is shown in Fig. 3. The figure indicates that 66 records were indexed only in Scopus, 11 records were indexed only in Web of Science, and 58 records appeared in both databases. This confirms that the use of both databases was necessary to improve the coverage of the RCCs literature. If only one database had been used, a considerable number of relevant records would have been missed. At the same time, the review showed that Scopus and Web of Science did not cover all relevant RCCs studies. Therefore, backward reference checking and supplementary searching were also used to identify older or differently indexed studies that were important for the technical discussion.

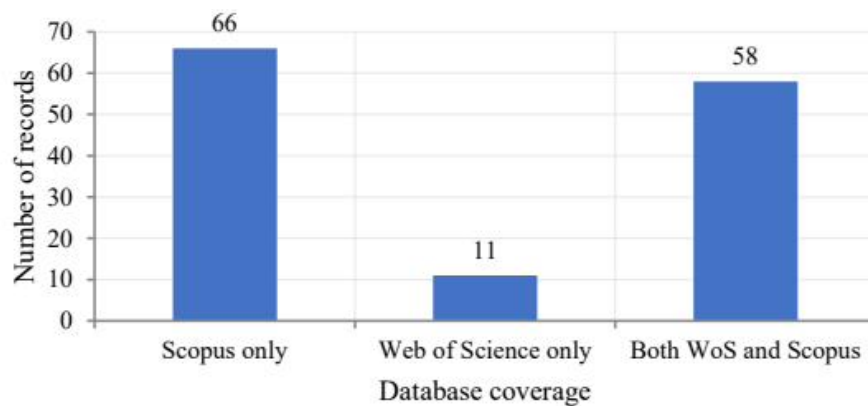


Fig. 3. Database coverage among the 135 unique indexed records after duplicate removal

3.3 Research and Source Categories

The distribution of research-category tags is presented in Fig. 4. These tags are descriptive and non-exclusive, meaning that one study may contribute to more than one theme. Most records are associated with structural engineering, civil engineering, mechanics, concrete materials, computational modelling, and construction-related sources. This distribution reflects the multidisciplinary nature of RCCs research, which combines structural behavior, material properties, reinforcement detailing, numerical modelling, design-code evaluation, and ML-based prediction.

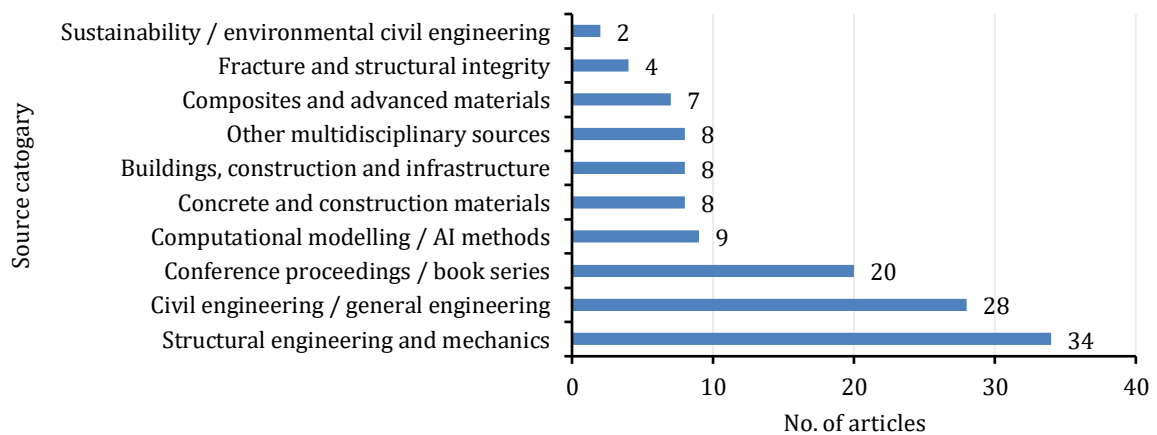


Fig. 4. Main research/source-category tags identified during screening

3.4 Main Research Themes

The selected literature can be grouped into several recurring themes: experimental investigation of shear behavior, influence of geometric and reinforcement parameters, special concrete and fibre-reinforced corbels, strengthening and repair, strut-and-tie modelling, comparison with design codes, numerical simulation, and ML-based prediction. This thematic structure shows that RCCs research has moved from early experimental observation and empirical design equations toward a broader combination of experimental, analytical, numerical, rehabilitation, and data-driven approaches.

In general, the descriptive analysis confirms that RCCs research remains active because of the complex stress-transfer mechanism in short shear-span members. The selected studies provide a broad basis for reviewing the influence of key parameters on shear capacity and for evaluating the role of explainable ML. However, the diversity of study types also confirms the need to distinguish between the qualitative review corpus and the smaller, more controlled dataset used for ML analysis.

4. Systematic Synthesis of RCCs Behavior

The systematic synthesis focuses on the main behavioral issues reported in the selected literature. RCCs behave as discontinuity regions, where the applied load is transferred mainly through a diagonal compression strut between the loading point and the column face [23]-[26]. Most building code provisions focus primarily on in-plane response; consequently, typical reinforcement details (Fig. 5) are proportioned to resist combinations of vertical shear and co-existing horizontal restraint forces. The reinforcement configuration consists of three key components:

- Primary reinforcing bars (A_{sc}): These bending reinforcing bars shall be securely anchored to ensure they achieve the yield strength (f_y) completely beneath the applied vertical load (V_u). To meet this requirement, satisfactory anchorage at the outer end can be obtained by welding a rebar of equal diameter across the ends of the primary tension rebars and developed by a 90° hook at the column for enhanced anchorage.
- Closed ties (A_h): Comprising hoop ties or stirrups, this reinforcement confines compression struts and counteracts splitting forces parallel to the thrust. As per ACI 318-25 guidelines, A_h shall be evenly spaced across $2d/3$ measured from primary rebars, positioned parallel and adjacent to the primary reinforcement (A_{sc}).
- Framing bar: This rebar, normally with a diameter similar to that of the ties, is used to anchor and fix the closed ties at the outside face.

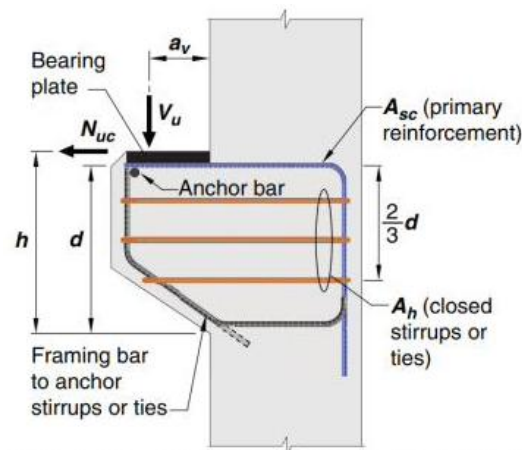


Fig. 5. Typical cross-section: rebars detailing and applied loads [9], [27]

Extensive research has identified several failure modes in corbels [15], which are dependent upon factors such as reinforcement detailing, geometry, material properties, and loading conditions. These modes include:

- Flexural failure: This failure occurs when the main rebars yield under excessive bending stress, as illustrated in Fig. 6(a).

- Shear-induced diagonal failure: In this failure, cracks initiate at the stressed zone under applied load and propagate diagonally toward the area where corbel and column meet, as depicted in Fig. 6(b).
- Shear friction failure: Characterized by near-vertical cracks originating at the upper junction and propagating primarily in a vertical direction toward the bottom fibres, as captured in Fig. 6(c).
- Anchoring splitting failure: This occurs due to insufficient support in the free end zone, as shown in Fig. 6(d).
- Bearing failure: Results from concrete crushing beneath the load-bearing area [38] due to inadequate proportioning of the bearing area, as demonstrated in Fig. 6(e).
- Vertical splitting failure: Typically caused by direct tension resulting from horizontal loads, detailed in Fig. 6(f).

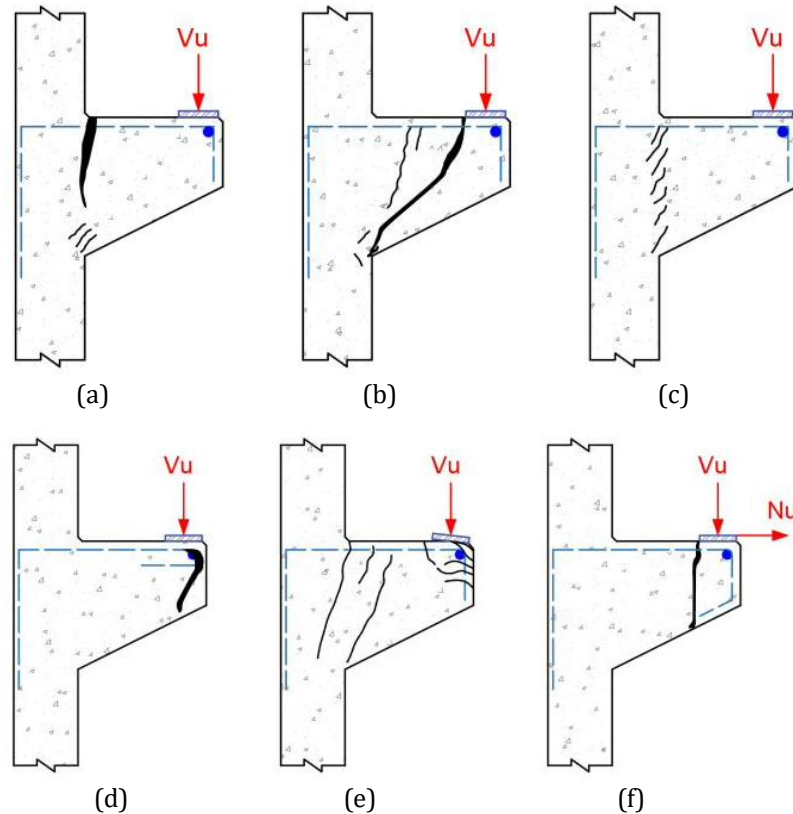


Fig. 6. Failure modes: (a) Flexure, (b) Diagonal shear, (c) Sliding shear, (d) Anchor lack, (e) Local crushing, and (f) Direct tension

These six modes are not equally likely in every situation; which of them governs depends on the application and on the load, condition imposed on the member. Under pure vertical loading with a small a/d ratio, the load reaches the column mainly through a steep compression strut, so the governing mechanisms are those associated with the strut and its end regions, namely diagonal splitting, local crushing beneath the bearing plate, and sliding shear along the column interface. As a/d increases, the strut flattens, flexural action grows in relative importance, and the observed mode migrates towards flexural yielding of the main tie and beam-type diagonal cracking; Lei et al. [44] recorded precisely this migration, from shear sliding at $a/d = 0.35$ to shear rotation at $a/d = 0.96$. When a direct horizontal force acts together with the vertical load, the picture changes qualitatively rather than quantitatively: the tie demand increases, additional moment is transferred at the corbel-column interface, and vertical splitting driven by direct tension becomes credible, which is the reason it is listed as mode (f) and the reason such specimens were excluded from the vertical-load corpus of this review. Kriz and Rathes [15] further observed that crack-control reinforcement becomes progressively less effective as the N/V ratio rises. Reinforcement detailing shifts the outcome in a similar way. Corbels without horizontal stirrups tend towards sudden diagonal splitting, whereas adequate horizontal reinforcement allows the tension tie to yield first

and converts the response into a more ductile flexural or beam-shear mode [17]; anchoring splitting failure, mode (d), is essentially a detailing failure at the free end rather than a strength deficiency of the section. Material choice acts in the same direction, since higher concrete strength raises capacity but increases brittleness unless fibres or hybrid reinforcement are provided, which can move the failure from diagonal splitting to flexural-shear [79]. Finally, the loading history matters in service applications. Corbels supporting crane girders or subjected to seismic action experience repeated or cyclic demand, under which stiffness degradation, bond slip, and progressive crack widening accumulate, so the governing limit state may be serviceability or fatigue-related deterioration rather than the monotonic failure modes of Fig. 6. In precast frames the same member also carries erection and restraint effects at the joint, which is why interface and anchorage modes are reported more often in that application than in isolated laboratory specimens.

4.1 Shear Transfer Mechanism

The shear response of RCCs is strongly influenced by the a/d ratio, which governs the transition in failure modes. According to Wight and MacGregor (2009) [28], this shift typically occurs within the range of 2.0-2.5. Members with a/d ratios greater than 2.5 are considered thin, while those with smaller ratios are classified as deep or non-thin [29]. Borgohain (2023) [29] demonstrated that the a/d ratio has a pronounced effect on shear strength, as illustrated in Fig. 7. When the ratio falls below 2.5, the shear stress at failure increases sharply, indicating a change in the dominant shear transfer mechanism.

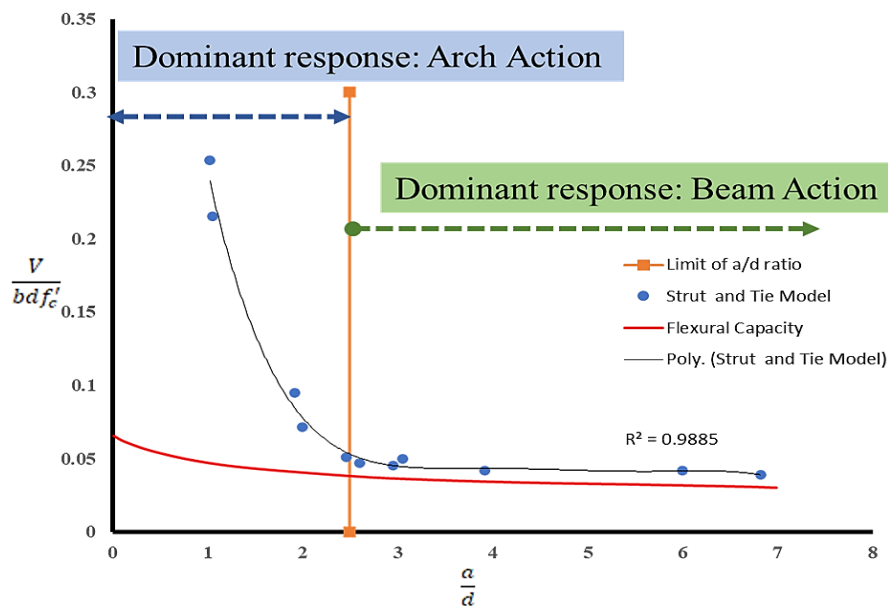


Fig. 7. Effect of shear span-to-effective depth ratio on shear capacity [29]

Because of these behavioral differences, distinct analytical approaches are adopted. Sectional flexural and shear models are generally applied to thin members ($a/d > 2.5$), whereas strut-and-tie (STM) models are more suitable for deep members ($a/d \leq 2.5$), as further discussed in Section 4.2.

Early experimental and analytical investigations into RCCs were carried out by Kriz and Rath (1965) [15] using NSC; their study examined the effects of reinforcement ratio, a/d ratio, concrete strength, and the N/V ratio. They reported that vertical tension reinforcement and horizontal stirrups contributed similarly to corbel strength under vertical loading, while the application of horizontal loads significantly reduced capacity. With the addition of supplementary reinforcement, the observed failure mechanisms tended to converge into a beam-shear type, characterized by the formation of diagonal cracks and subsequent crushing of the strut in compression. The researchers also identified the stress level at which bearing failures developed, concluding that the ultimate nodal strength was approximately $0.34f_c$ for larger a/d ratios. Moreover, they noted that the crack-control reinforcement becomes less effective as the N/V ratio rises.

Recently, studies have addressed various aspects, with their key points summarized as follows:

Mohamed et al. (2025) [30] cast nine fibre-reinforced double corbels to study torsional response under centric and eccentric vertical loads. They recorded first-crack load, ultimate torque, twist angle, displacements, crack patterns and toughness. Results showed that adding vertical and horizontal stirrups increased ultimate torque by about 4.6-18.0%, and widening the corbel raised torque by about 24.3%. Reducing eccentricity from $a/d = 0.75$ to 0.50 lowered cracking load and torque by about 10.7% and 26%, respectively. The study concluded that more stirrups and larger width improve cracking and torsional strength.

Amaral et al. (2025) [31] proposed a novel topology optimization for the design of two-sided RCCs in D-regions under multiple load cases [32], with the aim of achieving lightweight yet structurally reliable designs. Reinforcement areas were determined from the sum of principal forces in finite elements classified as steel, analogous to the STM. A representative result of this approach is shown in Fig. 8, which presents an optimized double-sided corbel with an a/d ratio of 0.59 and illustrates the proposed two-loop steel reinforcement layout. Nonlinear analyses that included both geometric and material nonlinearity were carried out using Abaqus. Although the optimized design showed lower stiffness and strength compared with designs based on the STM method, it still met the required load levels and consistently failed in shear, which was mainly controlled by material volume limitations.

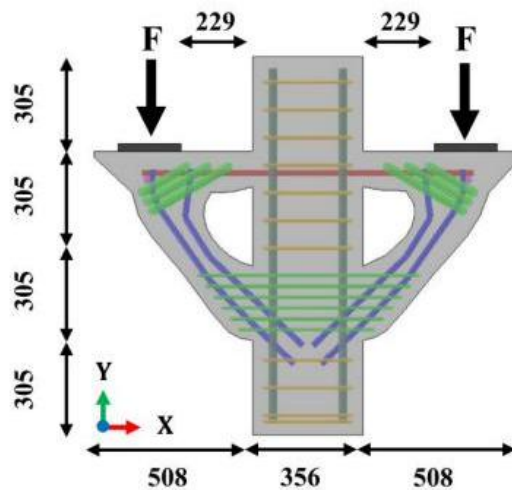


Fig. 8. Optimised corbel ($a/d=0.59$) with reinforcement [31]

Kheyroddin et al. (2025) [33] investigated how changing the arrangement of CFRP, rather than increasing the amount of secondary steel reinforcement, can improve the performance of RCCs using nonlinear finite-element analysis. Two horizontal reinforcement ratios, 0.33% and 0.52%, were analyzed together with a fixed CFRP layout, while a reference model with $\rho_h = 0.18\%$ was also considered. They found that changing the CFRP arrangement alone yielded up to a 33% increase in bearing capacity with the same material volume, while elevating ρ_h to 0.33% and 0.52% resulted in further gains of 5.52% and 11.55%, respectively. The authors conclude that optimizing CFRP configuration notably enhances post-yield bearing capacity.

Huang et al. (2025) [34] investigated how the inclination angle of main reinforcement and stirrups affects the shear performance of RCCs, using both experimental testing and nonlinear finite-element modelling via a concrete damage plasticity (CDP) framework. Two corbel specimens with reinforcement angles of 0° and 15° were tested under vertical loading in a quasi-static setup. The 15° inclination improved shear behavior markedly: yield load rose by 28.3%, ultimate load by 23.6%, strain in main reinforcement dropped by 51.3%, and stirrup yield load increased by 11.6% while its strain level at 250 kN decreased by 23.7%. The CDP model replicated crack development and failure modes accurately, with less than 2.27% error in ultimate load prediction. The authors derived a modified triangular-truss model, Fig. 9, incorporating reinforcement inclination and developed a functional correlation between inclination angle and bearing capacity that aligns closely with test data.

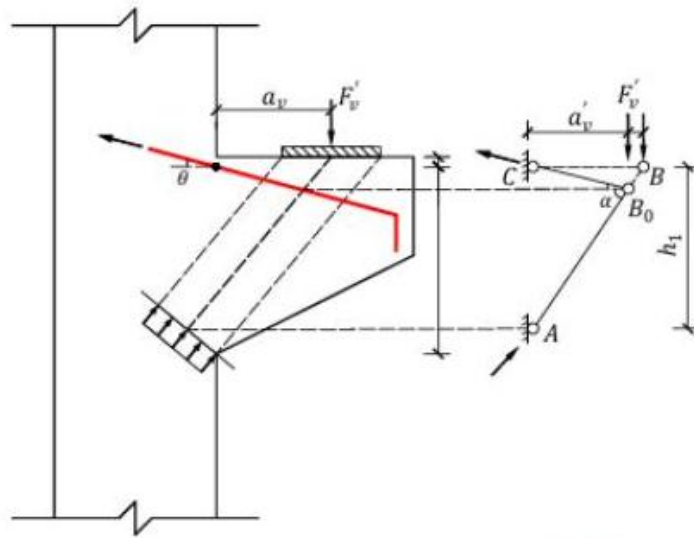


Fig. 9. Modified triangular truss model [34]

Naser et al. (2025) [35] investigated the structural performance of 20 RCCs with different levels of recycled coarse aggregate (RCA) to study the mechanical properties [36]-[38]. The study concluded that replacing natural aggregate by 20%, 40% and 60% reduced compressive strength by about 5.2%, 10.4% and 14.0% and lowered ultimate load by about 4.4%, 8.6% and 16%. Also, higher reinforcement ratios enhanced capacity and stiffness while mitigating deflection, whereas increased RCA content and a/d ratios amplified load-deflection responses. Crack patterns were similar to natural aggregate specimens and energy dissipation was largely unaffected. Prediction using ACI 318 provisions tended to be more conservative compared with experiments.

4.2 Effect of a/d Ratio

The shear a/d ratio significantly influences the structural behavior of elements, particularly affecting shear strength and the development of cracks [39], [40]. A decrease in the a/d ratio generally leads to an increase in the cracking load. For instance, a reduction in the a/d ratio from 0.7 to 0.3 can result in an average increase in cracking load of 155% [41]. Similarly, when the a/d ratio decreases, the cracking loads for corbels with consistent properties tend to increase [41]. This phenomenon is attributed to the decreased moment due to decreasing the distance between supports and applied loads, which enhances the effectiveness of the arching mechanism by transmitting a larger portion of the load directly to the support through a diagonal compression strut [29]. Conversely, an increase in the a/d ratio leads to a greater number of vertical and inclined cracks [42].

The conventional and the proposed corbel specimens in the work of Abdul-Razzaq and Dawood (2020) [43] demonstrated a reduction in ultimate strength with increasing a/d ratio. The results showed that for $a/d = 0.5$, the predicted ultimate capacities using SF and STM were 15% and 22% lower than the experimental failure load, while for $a/d = 1$ these differences increased to 18% and 27%, and for $a/d = 1.5$ they reached 32% and 37%, respectively. Flexural cracks initiated at approximately 19%, 11%, and 12% of the failure load for $a/d = 0.5$, 1, and 1.5, whereas diagonal cracks developed at about 34%, 33%, and 30%, respectively. The authors concluded that STM provides more reliable predictions than SF, particularly when a/d lies between 1 and 2, due to its ability to better represent the failure mode.

Similar findings were obtained in the work of Lei et al. (2025) [44], in which the corbels were reinforced with inclined steel rebars at a/d ratios of 0.35, 0.61, and 0.96. The most important result is the inverse relationship between the shear strength and the a/d ratio, along with the change in failure mode from shear sliding at lower ratios to shear rotation at higher ratios. For example, the

specimen tested at $a/d = 0.35$ carried a load of 940.3 kN, while the specimen with $a/d = 0.96$ resisted only 323.4 kN. These results confirm that the a/d ratio plays a key role in controlling both the ultimate strength and failure behavior of RCCs.

It should also be noted that increasing the a/d ratio generally leads to a reduction in shear strength. The vertical stirrups improve cracking behavior and contribute to the experimental shear resistance; however, the stirrup effectiveness depends strongly on the a/d ratio and the inclination of the compression strut. For very short corbels, where a/d is less than or equal to one, the dominant resistance is mainly provided by direct strut action, and the contribution of vertical stirrups to ultimate strength is limited. As the a/d ratio increases, the internal load path becomes less direct, and vertical stirrups become more active in controlling diagonal cracking and shear transfer. This behavior is clearly depicted in Fig. 10.

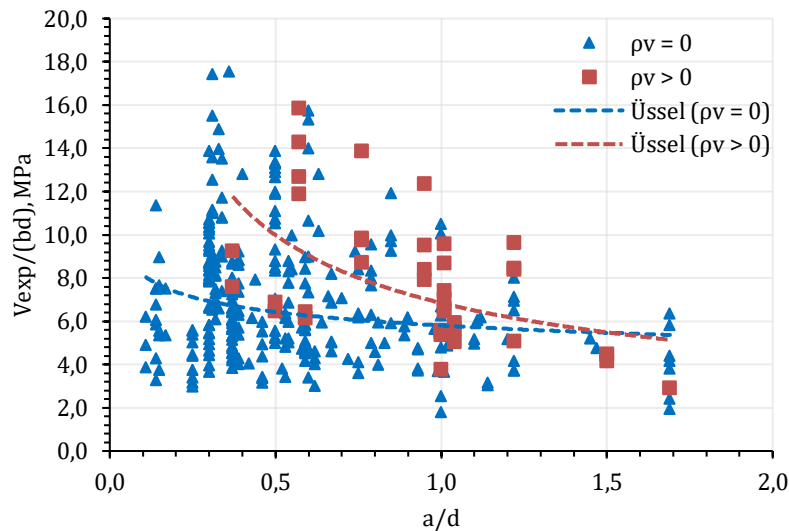


Fig. 10. Influence of a/d ratio on RCC shear strength, with and without vertical stirrups

4.3 Effect of Column Load

Few studies, in terms of structural response, ultimate strength, and crack development, have been found. Early research suggested that axial load applied on the column might interact with corbel loading, which possibly changes the strength [15]. These initial investigations treated additional column load as an important variable affecting the response of corbels [15]. However, later experiments questioned this view, indicating that concentric column loads had little impact on overall corbel strength [45], [46].

Further tests using different reinforcement types and specimen layouts confirmed these results. Corbels with conventional steel bars or steel fibres consistently showed no major change in ultimate strength due to column loading. As a result, many researchers began applying loads directly to corbels, ignoring column load effects [45], [47]. Although strength was not greatly affected, column load was found to influence serviceability behavior, especially cracking. In particular, the presence of column load delayed the onset of cracking and reduced crack widths at the column-corbel connection, which improved crack control and durability [45], [48].

A thorough study performed by Fattuhi (1990) [45], considered one of the most detailed experiments on column load effects, tested corbels with both conventional and steel fibre reinforcement. Based on tests of eight specimens subjected to concentric axial loads, the study reported no noticeable influence of column load on ultimate strength, supporting earlier conclusions by Kriz and Rath (1965) [15]. However, the results highlighted serviceability advantages, as column load delayed the first crack and reduced crack widths at the corbel-column junction. These findings support the general view that column loads have little effect on ultimate capacity but play an important role in cracking behavior and durability.

4.4 Effect of Vertical Stirrups

Vertical stirrups in RCCs mainly affect resistance to diagonal cracking, deformation capacity, and service performance. Their influence on ultimate load strength remains dependent on the geometry of the corbel, especially the a/d ratio and the inclination angle of the compression strut. From a structural perspective, vertical stirrups help restrain the lateral expansion of the diagonal compression strut, increase the load required to initiate diagonal cracking, and delay sudden failure [49], [50]. The test results generally reflect this behavior, showing that a higher vertical stirrup ratio improves both the cracking load and the ultimate load [51]-[55]. In some specimens, an improvement in strength of more than 20% was reported [49]. Furthermore, the presence of vertical stirrups leads to a more uniform crack pattern and better ductile behavior. In contrast, corbels without this reinforcement display less deformation capacity [50]. Despite these advantages, some studies indicate that vertical stirrups may still produce a brittle failure response when compared to horizontal reinforcement [56].

On the other hand, the parameter that controls the effectiveness of the vertical stirrups in addition to the inclined angle includes the a/d ratio of the corbel. When a/d is less than or close to unity, the compression strut is steep and the load is transferred more directly from the bearing region to the column face. Under this condition, the ultimate shear resistance is governed mainly by the concrete strut and the main tension tie, so the additional contribution of vertical stirrups may be limited. As the a/d ratio increases, the strut becomes less steep and diagonal cracking becomes more critical. Therefore, vertical stirrups become more effective in controlling crack propagation and improving shear resistance [43], [57], [58]. This interpretation explains why some STM formulations do not explicitly include the vertical stirrup contribution, while experimental studies still report improvements in cracking behavior and, in some cases, ultimate capacity [59]-[61].

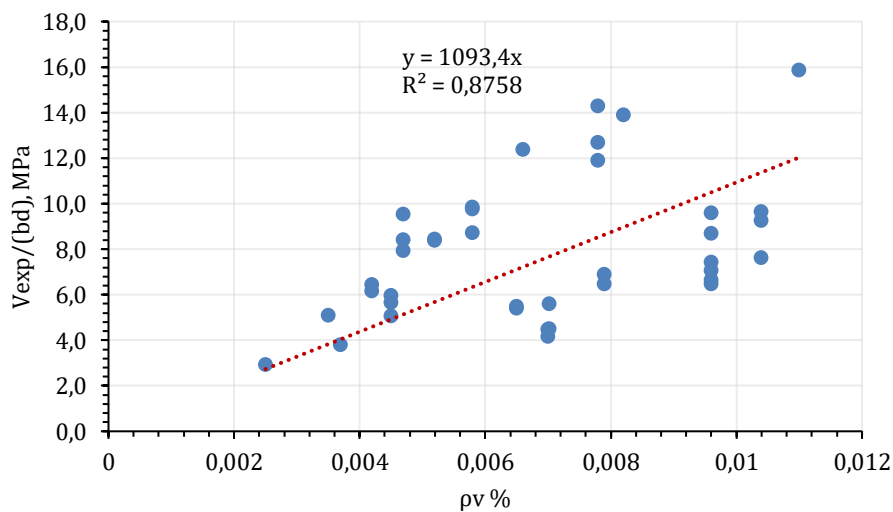


Fig. 11. Influence of vertical stirrups on RCC shear strength

Through the activation of a larger portion of the concrete volume in shear transfer, vertical stirrups also improve the stability of the internal force path and reduce the softening of the compression strut [62], [63]. Although these benefits were noted in the literature, concerns about their reliability have been expressed for many years because the first investigations warned against unsafe behavior due to excessive reliance on vertical stirrups [15].

A detailed series of experiments was conducted by Li et al. (2023) [49] to further clarify the influence of the vertical stirrups on the structural performance of RCCs. The results demonstrated a direct correlation between the ratio of vertical stirrups and the structural performance. An increase in the vertical stirrup ratio from 0.39% to 0.785% resulted in a 23.7% increase in the diagonal cracking load and a 22.6% increase in the ultimate capacity. The authors attributed these improvements mainly to the ability of vertical stirrups to restrain transverse strain within the compression strut, which delays crack formation and improves ductile behavior. At the same time,

the study reported that vertical stirrups had only a minor effect on cracking load related to normal section behavior. This balanced finding emphasized both the advantages and the limits of vertical stirrups and provided a useful reference point for later analytical and design studies. In addition, the presence of vertical stirrups leads to a proportional increase in shear strength capacity, as illustrated in Fig. 11.

4.5 Effect of Horizontal Stirrups

Horizontal stirrups are commonly provided in RCCs to increase shear strength, improve ductile behavior, and reduce the risk of brittle failure [17,62,64]. Their main role is to delay the formation of diagonal tension cracks by confining the concrete core at the connection, leading to increased bond strength, and then allowing the primary tensile reinforcement to reach yielding. As a result, failure is more likely to shift from sudden splitting to more ductile modes, such as flexural or beam-shear failure [17,65,66]. Experimental studies have reported clear gains in both strength and deformation capacity. In some cases, horizontal stirrups increased the vertical failure load by up to 50% [59], while significant improvements in toughness and strain ductility, reaching up to 511%, were observed in steel fibre-reinforced RCCs [42]. In addition to those studies mentioned, several other research works have shown significant increases in shear capacities of corbels equipped with horizontal stirrups; specifically, capacity increases were found to be between 15% and 46% over those that did not include horizontal stirrups [35,67]. The results collectively provide support for the necessity of including an adequate number of horizontal stirrups to preclude brittle failure [15], [58].

However, it has been shown that the effectiveness of horizontal reinforcement depends heavily on both the a/d ratio and the manner in which the corbel is loaded. For example, when a/d ratios are low (less than or equal to 0.9) and the angle of the compression strut exceeds 45° , horizontal reinforcement plays a major role in transferring loads across cracks and controlling crack propagation [17,59]. In contrast, for $a/d = 1.0$, its contributions to shear capacity have been considered minimal [58]. Horizontal reinforcement may provide relatively little enhancement of shear capacity when corbels are subjected to combined vertical and horizontal loading; under such conditions, horizontal reinforcement has been described as reserve strength due to confinement rather than a primary load-carrying mechanism [15,59]. More recently, researchers have noted the influence of horizontal reinforcement on torsion behavior; they report that increasing amounts of horizontal reinforcement can lead to increases in ultimate torque of as much as 13.3% [30]. Yet, in over-reinforced specimens, their contribution diminishes, mainly serving to mitigate concrete softening rather than significantly increasing shear strength [62].

Beyond their role in capacity, horizontal stirrups serve a critical serviceability function by enhancing crack control, reducing deformation, and improving stiffness. They confine the concrete, redistribute stresses, and reduce crack widths particularly for corbels with small a/d ratios [53], [68]. Experimental findings report ultimate load increases between 19% and 27% in fibre-reinforced corbels with stirrups [65], while other studies found cracking load improvements of up to 34.78% with increased stirrup ratios [69]. However, beyond certain reinforcement thresholds, especially in high-strength concrete, further increases in stirrup content produce limited strength gains [41]. Importantly, compared to vertical stirrups, horizontal loops are generally more effective because they intercept the steep diagonal cracks, thus reducing brittleness and yielding a safer, more predictable failure mechanism [15,56].

Mattock et al. (1976) [17] conducted one of the earliest systematic experimental programmes on RCCs, establishing the fundamental role of horizontal stirrups in controlling shear behavior and preventing brittle failures. Their tests demonstrated that the absence of stirrups often led to diagonal splitting, while their inclusion enabled the tensile reinforcement to yield, producing flexural or beam shear failures considered acceptable in design practice. They also introduced a design expression for the minimum required horizontal reinforcement area [70], $A_h \geq 0.5(A_s - A_n)$, and recommended its distribution within the upper two-thirds of the effective depth adjacent to the main tension reinforcement. Furthermore, they showed that the horizontal stirrup contribution varied with a/d , becoming negligible at $a/d = 1.0$ but highly effective when $a/d < 0.9$. Their findings

remain foundational, informing subsequent research and influencing modern code provisions for corbel design.

Furthermore, the inclusion of horizontal stirrups proportionally improves the RCC shear strength whether the horizontal force exists or not, as shown in Fig. 12.

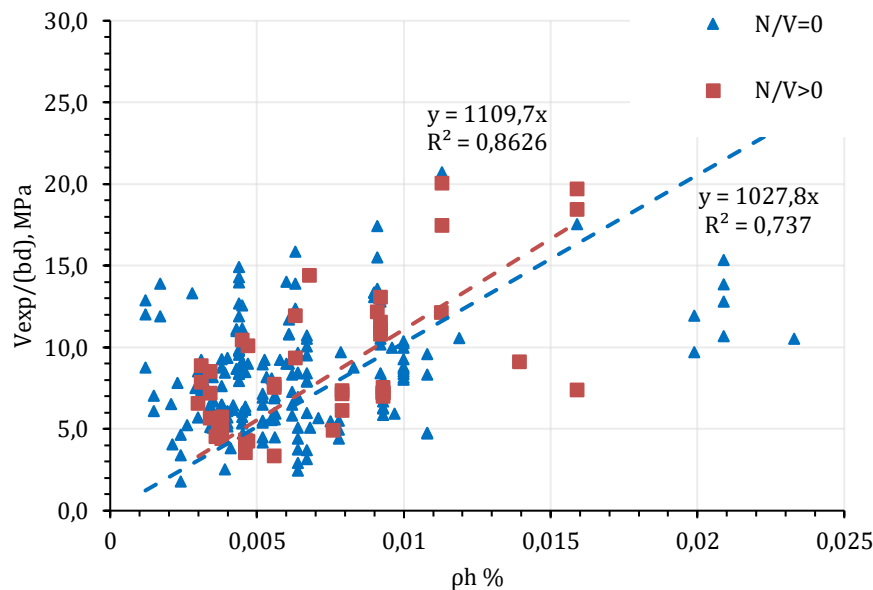


Fig. 12. RCC shear strength vs. horizontal link ratio under vertical and combined loading

4.6 Effect of Concrete Compressive Strength

Concrete compressive strength (f_{ck}) is a fundamental parameter controlling the load-carrying capacity, shear resistance, stiffness, and failure mode of RCCs [41,49,50,71-75]. Increasing f_{ck} generally enhances the shear capacity, cracking load, and ultimate load, with reported improvements ranging from 20% to over 65% depending on reinforcement and a/d ratios [42], [76,77]. Corbels made from high-strength concrete show higher longitudinal steel strain and ductility [78] in addition to energy absorption and flexural toughness as well as higher stiffness and a more gradual load-deflection relationship due to higher strength concrete [76,79].

It is difficult to determine how changes in f_{ck} affect failure modes. The addition of higher strength concrete may cause corbels to become more brittle; however, the addition of fibres or hybrid reinforcement will reduce that risk and can change the failure mode from diagonal splitting to a flexural-shear failure [79-84]. The influence of compressive strength also varies with geometry: for larger a/d ratios, its effect on peak load may lessen, whereas in steel-fibre and hybrid high-strength concrete corbels [85], higher f_{ck} consistently improves ultimate capacity [40,86,87].

Design models show that increasing f_{ck} generally improves safety margins in code-based STMs, though results differ between standards [67]. Experiments further reveal that corbels with higher concrete strength can have up to 58% greater shear and moment capacity than those with lower strength [88]. In general, concrete compressive strength remains the key factor governing corbel behavior, mainly because it resists compressive forces [88].

Al-Allaf et al. (2024) [79] adopted a parametric study on hybrid corbels to measure how concrete strength affects stiffness, energy absorption, and failure mode. By varying f_{ck} from 30 MPa to 50 MPa, they observed energy absorption increases of 114-173% and a shift in failure mode from diagonal splitting to flexural-shear at 40 MPa, with some return toward splitting at 50 MPa. The study underlined the interaction between concrete strength, a/d ratio, and reinforcement quantity, concluding that while higher f_{ck} improves performance, fibres may be needed to offset increased brittleness.

Based on the dataset available from the literature, Fig. 13 illustrates the relationship between the square root of the concrete compressive strength and the experimental shear strength for RCCs. The trend line shows a positive correlation between the two variables. The regression equation, with a high coefficient of determination ($R^2=0.9107$), indicates that the experimental shear strength is strongly influenced by the concrete compressive strength.

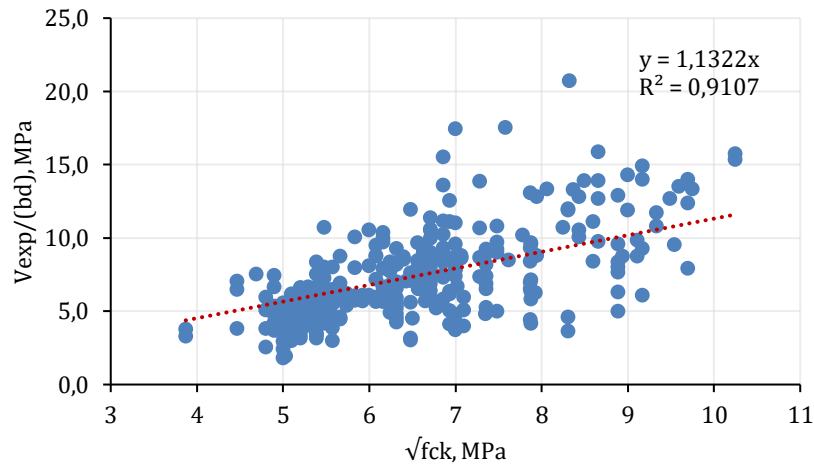


Fig. 13. Variation of RCC shear strength with concrete compressive strength

4.7 Effect of Longitudinal Reinforcement Ratio

The longitudinal reinforcement ratio (ρ_f), often referred to as the main tension reinforcement ratio, is a critical factor influencing the ultimate load capacity, stiffness, ductility, and failure mode of RCCs [35,49,50,89,90]. Increasing ρ_f generally enhances the ultimate load and shear strength, with reported gains ranging from 6% to over 40% depending on concrete type, a/d ratio, and secondary reinforcement amount [35,49,77]. Numerical models show that shear strength rises sharply with longitudinal steel ratios up to 1.3%, beyond which the effect exhibits diminishing returns [91].

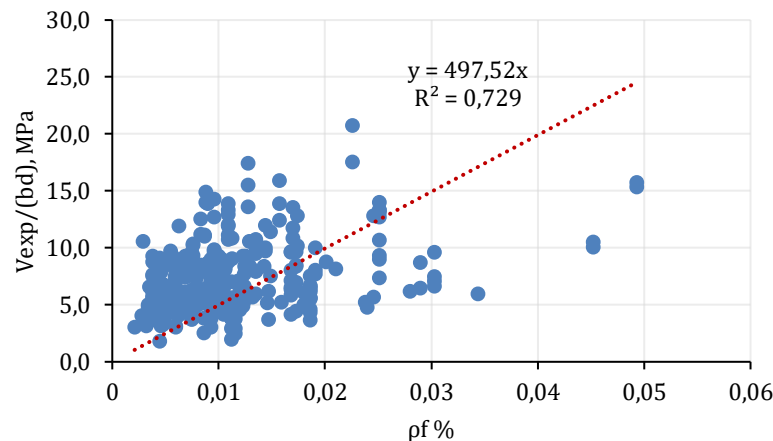


Fig. 14. Correlation of RCC shear strength with tensile reinforcement ratio

The longitudinal reinforcement also governs cracking behavior and ductility. Increasing ρ_f raises the inclined section cracking load while having a minor effect on the normal section, and promotes wider and longer flexural cracks along the corbel-column interface [49,73,77]. Low reinforcement ratios lead to yielding of the steel before concrete crushing, resulting in ductile failure, whereas high ratios may induce brittle failure dominated by strut crushing or nodal failure [53,64,92]. Under initial loading, the concrete carries most of the stress, but post-cracking, the longitudinal reinforcement governs the bending response and impacts the depth of the compression block [49], [61]. Serviceability aspects, including deflection and crack width, are also affected by ρ_f , and

analytical models incorporate it alongside other parameters to predict corbel performance accurately [39,93].

Li et al. (2023) [49] experimentally investigated steel-fibre RCCs, demonstrating that increasing ρ_f from 0.55% to 0.98% enhanced ultimate loads by up to 19.4% and raised inclined section cracking loads by 33.3%. Strain measurements showed that, once concrete cracking occurs, the longitudinal reinforcement ratio ρ_f becomes more actively involved, through which ductility and internal stress redistribution are improved. As illustrated in Fig. 14, the shear strength of RCCs displays a clear and positive relationship with ρ_f , a trend that is mainly governed by flexural resistance rather than by shear transfer mechanisms such as dowel action. If the dowel action contribution were included, the correlation would likely become stronger.

4.8 Effect of k/h Ratio

The external depth to internal depth (k/h) ratio, which describes the relative depth between the free end of the corbel and the column interface, is not commonly considered as a primary parameter in existing studies because the failure in RCCs normally occurs at the column interface. However, the effect can be inferred through the geometric properties that govern corbel behavior. One of these most important properties is the a/d ratio, which is generally considered the dominant factor controlling both load capacity and governing failure mode [94]-[97]. The more recent studies that have examined the k/h ratio directly confirmed that an increase in k/h from 0.24 to 1.00 led to an 11.5% rise in ultimate shear capacity. This indicates that larger k/h values improve diagonal compression action and the efficiency of load transfer [77]. In line with this conclusion, Somerville (1974) [98] suggested that maintaining k/h within the range of 0.45-0.60 provides a balanced geometry, by which secondary failure mechanisms can be reduced [60].

This geometric interpretation is supported by the explainable ML results reported later in Section 7.4. The column width w_c ranked third in the SHAP importance list, with a mean absolute SHAP value of 0.0217 and a consistently positive effect direction (Table 12), and the corbel height h ranked first. Since the k/h ratio is defined by the same pair of depths that fix the tapered profile between the free end and the column face, a member proportioned with a larger k/h offers a deeper and better-supported nodal region at the interface, which is precisely the region whose size the model rewards through h and w_c . The SHAP evidence therefore reinforces, from an independent data-driven direction, the experimental observation of an 11.5% capacity gain as k/h increased from 0.24 to 1.00, and it explains why k/h should not be treated as a purely detailing-related quantity: it modifies the geometry of the compression field and of the support zone, which the model identifies as among the strongest contributors to predicted capacity. It also indicates that reporting k/h explicitly in future experimental programmes would allow this variable to be tested directly rather than inferred through correlated dimensional inputs.

In general, the reviewed studies show that the shear behavior of RCCs is controlled by a combined effect of geometry, concrete strength, reinforcement arrangement, and loading condition. Although each parameter has a distinct influence, its effect cannot be fully separated from the internal strut-and-tie mechanism. Table 7 summarizes the main behavioral trends identified from the reviewed literature and clarifies the practical implication of each parameter.

5. Strengthening and Repair of RCCs

Although the main part of this review focuses on original RCCs and their shear behavior under vertical loading, strengthening and repair studies form an important related branch of the literature. In practice, corbels may require strengthening because of increased service loads, construction defects, insufficient detailing, material deterioration, accidental damage, or changes in use. Since corbels are usually located at highly stressed support regions, any local weakness may strongly affect the load path between the applied load and the column face. For this reason, several researchers have examined different strengthening techniques, including externally bonded CFRP sheets [109-112], near-surface-mounted reinforcement [113], steel plates [114-116], basalt-fibre systems [117], post-installed composite fabrics [118], and local repair using fibre-reinforced materials [59,119].

Table 7. Summary of the main parameters affecting RCCs shear behavior

Parameter	General effect on shear behavior	Main interpretation	Practical implication
Shear span-to-effective depth ratio, a/d	Increasing a/d generally reduces shear strength and changes the failure mechanism.	Small a/d values promote direct compression-strut action, while larger values increase flexural and diagonal cracking effects.	The a/d ratio should be treated as one of the primary controlling variables in design and prediction models.
Concrete compressive strength, f_c' or f_{ck}	Higher concrete strength usually increases cracking load, stiffness, and ultimate shear capacity.	The concrete compression strut and nodal zones become stronger as concrete strength increases.	Higher-strength concrete improves capacity, but may increase brittleness if not accompanied by adequate reinforcement or fibres.
Corbel width and depth	Larger dimensions generally increase the load-carrying capacity.	Wider and deeper corbels provide a larger stress-transfer area and improve the efficiency of the compression field.	Size-related variables should be included in predictive models, especially when the output is ultimate load rather than normalized stress.
Longitudinal reinforcement ratio, ρ_f	Increasing ρ_f improves tensile-tie resistance, stiffness, and ultimate capacity up to a certain level.	The main reinforcement forms the tension tie in the strut-and-tie mechanism and helps maintain equilibrium after cracking.	Excessive longitudinal reinforcement may reduce ductility and shift failure toward concrete crushing or nodal distress.
Horizontal reinforcement ratio, ρ_h	Horizontal stirrups improve crack control, ductility, and shear capacity, especially for short corbels.	Horizontal reinforcement intercepts diagonal cracks and confines the disturbed region near the corbel-column interface.	Adequate horizontal reinforcement is needed to reduce brittle splitting and improve post-cracking behavior.
Vertical reinforcement ratio, ρ_v	Vertical stirrups improve diagonal crack control and deformation capacity, but their strength contribution depends on a/d .	Their effect is limited in very short corbels dominated by direct strut action, but becomes more active as diagonal cracking becomes more pronounced.	Vertical stirrups should be considered mainly as crack-control and ductility-enhancing reinforcement, with careful interpretation in strength models.
Column load	Usually has limited influence on ultimate shear capacity, but can improve cracking behavior.	Axial compression may delay crack initiation and reduce crack width at the corbel-column junction.	Column load should not be assumed to significantly increase ultimate capacity unless supported by specific test evidence.
Loading history	Repeated or cyclic loading may reduce stiffness, increase deflection, widen cracks, and reduce ultimate capacity.	Damage accumulation, bond slip, and progressive cracking modify the internal load-transfer path.	Corbels subjected to crane, seismic, or repeated service actions require additional attention to ductility and crack control.
Strengthening and repair	CFRP, NSM reinforcement, steel plates, and fibre-based systems can increase capacity and stiffness.	Strengthening provides additional tensile resistance and crack bridging, but may introduce debonding or brittle failure.	Strengthened corbels should be interpreted separately from original unstrengthened specimens in databases and design models.

CFRP strengthening has received the greatest attention because it can be applied externally with limited change to the member geometry [120]. Al-Kamaki et al. [109] investigated the behavior of RCCs strengthened with CFRP sheets, while Abdulrahman et al. [110] examined the use of CFRP to improve the performance of high-strength RCCs. Similar studies by Assih et al. [111] and Ivanova et al. [112] also showed that externally bonded carbon-fibre fabrics can increase the capacity of damaged or deficient corbels. These studies generally indicate that CFRP strengthening improves load capacity and crack control by providing additional tensile resistance across the critical cracking zone. However, the effectiveness of this method depends strongly on bond quality, anchorage length, fibre orientation, and the ability of the strengthening layer to remain attached until high load levels are reached.

A recurring issue in CFRP-strengthened corbels is premature debonding. Ivanova et al. [121] studied the influence of anchorage length of composite fabrics and showed that the strengthening system cannot be assessed only by the amount of fibre material used. The development length, end anchorage, and local stress concentration near the corbel-column junction are also important. Ghozani et al. [122] further demonstrated through numerical modelling that different CFRP laminate layouts can lead to different stress-transfer patterns and failure responses. These findings suggest that strengthening design should not only aim to increase the nominal capacity, but should also control debonding, peeling, and local brittle failure.

Near-surface-mounted strengthening has also been used as an alternative to externally bonded sheets [123,124]. Shakir and Kamonna [125] studied high-strength self-compacting concrete corbels strengthened with NSM steel bars, while Shakir later examined retrofitting of high-strength self-compacting corbels using near-surface-mounted steel reinforcement. Ali and Abbas [126] also investigated lightweight concrete corbels strengthened with NSM-CFRP bars. Compared with externally bonded sheets, NSM systems can provide better protection to the strengthening material and may improve bond behavior because the bar or strip is embedded inside grooves cut into the concrete cover. Nevertheless, their performance still depends on groove dimensions, adhesive quality, bar anchorage, and the condition of the surrounding concrete.

Other researchers have explored steel plates, basalt fibres, and steel-fibre-based strengthening systems. Fadel and Waryosh [115] examined normal- and high-strength RCCs strengthened with steel plates, showing that plate strengthening can be useful where higher stiffness and direct force transfer are needed. Gülşan et al. [117] investigated the rehabilitation of normal and self-compacted steel-fibre-reinforced concrete corbels using basalt-fibre systems. Abdul-Alhassan and Kadhim [127] studied reinforced concrete brackets strengthened with steel fibre. These approaches show that the strengthening of corbels is not limited to FRP systems, and that material selection should depend on the type of deficiency, exposure condition, available anchorage length, and required ductility.

Analytical and numerical work has also supported the interpretation of strengthened corbel behavior. Campione and Cannella [128] proposed an analytical model for the flexural response of RCCs externally strengthened with FRP, while several finite-element studies used nonlinear modelling to describe crack propagation, stress redistribution, and damage development in strengthened specimens. These studies are useful because direct experimental testing of every strengthening layout is difficult, especially when the behavior involves concrete cracking, bond slip, fibre rupture, debonding, and local crushing.

Comparable numerical evidence from adjacent member types supports the same conclusion. Abbas et al. [129] applied a concrete damage plasticity model to RC beams strengthened with high-performance concrete (HPC) under torsion, and Abbas and Hamzah [130] examined hybrid concrete T-beams in which HPC was used to remedy deteriorated sections. Both identify the interface between the original and the added material as the quantity controlling the response, which is the same requirement established for bonded and NSM systems in RCCs.

Because the effectiveness of a strengthening scheme is decided less by the material selected than by the way it is detailed, it is useful to set the individual studies side by side rather than to describe them in isolation. Table 8 therefore compiles the representative strengthening and repair case

studies retained in the review, giving for each one the condition of the corbel and the technique applied, the outcome as reported in the source, and the practical issue that governed that outcome.

Table 8. Representative strengthening and repair case studies reported in the reviewed literature

Case study	Corbel condition and technique	Reported outcome in the reviewed source	Governing practical issue
Al-Kamaki et al. [109]	Deficient RCCs strengthened with externally bonded CFRP sheets.	Externally bonded sheets increased load capacity and improved crack control by adding tensile resistance across the critical cracking zone.	Effectiveness controlled by bond quality and by the ability of the sheet to remain attached up to high load levels.
Abdulrahman et al. [110]	High-strength RCCs upgraded with CFRP.	CFRP improved the performance of high-strength corbels, confirming that the technique is not restricted to normal-strength concrete.	Higher concrete strength does not remove the sensitivity of the system to interfacial bond.
Assih et al. [111]; Ivanova et al. [112]	Damaged or deficient short corbels strengthened with bonded carbon-fibre fabrics.	Bonded fabrics increased the capacity of damaged or deficient corbels and modified crack development in the shear zone.	Local stress concentration close to the corbel-column junction.
Ivanova et al. [121]	Strengthened short corbels with varying anchorage length of composite fabric.	Performance could not be explained by the amount of fibre alone; development length, end anchorage, and local stress concentration were decisive.	Anchorage detailing rather than fibre quantity governs the achievable gain.
Ghozani et al. [122]	Numerical study of alternative CFRP laminate layup schemes.	Different laminate layouts produced different stress-transfer patterns and failure responses for the same member.	Layup configuration changes the failure sequence and must be designed, not assumed.
Shakir and Kamonna [125]; Shakir and Alsaheb [113]	High-strength self-compacting corbels strengthened and retrofitted with NSM steel bars.	Embedding the reinforcement in grooves protected the strengthening material and improved bond behavior relative to externally bonded sheets.	Groove dimensions, adhesive filling, and development length control the result.
Ali and Abbas [126]	Lightweight concrete corbels strengthened with NSM-CFRP bars.	NSM-CFRP was applicable to lightweight concrete corbels, extending the technique beyond normal-weight concrete.	Condition of the surrounding concrete cover limits groove performance.
Fadel and Waryosh [115]	Normal- and high-strength RCCs strengthened with steel plates.	Plate strengthening was effective where higher stiffness and direct force transfer were required.	Stress concentration, corrosion risk, added weight, and anchorage difficulty.
Gulsan et al. [117]; Abdul-Alhassan and Kadhim [127]	Rehabilitation of normal and self-compacted SFRC corbels using basalt fibre, and brackets strengthened with steel fibre.	Fibre-based rehabilitation improved strength and serviceability, showing that corbel strengthening is not limited to FRP systems.	Material selection must follow the type of deficiency, exposure, anchorage length, and required ductility.
Campione and Cannella [128]	Analytical model for the flexural response of FRP-strengthened corbels.	Provided a means of interpreting strengthened behavior without testing every possible layout.	Reliability depends on bond assumptions and validation against experiments.

Read as a group, these cases show a consistent pattern: successful strengthening in the reviewed literature is associated with a controlled force path into the strengthening element, that is, with

adequate development length, sound end anchorage, and a bond interface capable of surviving up to the intended load level. Al-Kamaki et al. [109] and Abdulrahman et al. [110] confirmed that externally bonded CFRP raises capacity in both normal- and high-strength corbels, but the comparison between Ivanova et al. [121] and Ghozani et al. [122] is more instructive, since the first shows that fibre quantity alone does not determine performance once anchorage length is varied, and the second shows that two layups of identical material can produce different failure responses. The near-surface-mounted cases [113,125,126] address the same difficulty from the opposite direction, by relocating the strengthening element into grooves where it is protected and better bonded, at the cost of introducing groove geometry and adhesive filling as new controlling variables. The steel-plate and fibre-based cases [115,117,127] extend the available options where stiffness or corrosion resistance governs the choice. The unifying practical lesson for rehabilitation design is that the target of the intervention should be the failure mechanism identified in the deficient member, not the nominal capacity alone, since every technique in Table 8 is capable of shifting the governing mode as well as raising the strength.

Table 9. Summary of strengthening and repair techniques for RCCs

Strengthening or repair technique	Main contribution	Typical advantages	Main limitations or failure concerns
Externally bonded CFRP sheets	Provides additional tensile resistance across critical cracking regions.	Increases ultimate load, improves crack control, and can be applied with limited change in member geometry.	Premature debonding, peeling, local stress concentration, and limited anchorage length may reduce effectiveness.
CFRP laminate or fabric anchorage systems	Improves the force transfer between CFRP and concrete.	Delays debonding and enhances the utilization of the strengthening material.	Performance depends strongly on anchorage length, end detailing, adhesive quality, and surface preparation.
Near-surface-mounted steel or CFRP bars	Adds embedded reinforcement near the critical tension zone.	Provides better protection than externally bonded sheets and may improve bond performance.	Requires groove cutting, proper adhesive filling, adequate development length, and sound surrounding concrete.
Steel plate strengthening	Provides high stiffness and direct force transfer.	Useful where large stiffness increases or local strengthening is required.	May cause stress concentration, corrosion risk, additional weight, and anchorage difficulty.
Basalt-fibre or composite fabric systems	Provides additional crack-bridging and tensile resistance.	Can improve strength and serviceability while offering corrosion resistance.	Bond failure and limited experimental data may restrict direct design application.
Steel-fibre or fibre-reinforced repair materials	Enhances local tensile resistance and crack control in damaged regions.	Improves toughness, crack resistance, and local repair performance.	Effectiveness depends on repair thickness, interface bond, fibre distribution, and damage level before repair.
Numerical and analytical strengthening models	Helps interpret stress transfer, crack propagation, and debonding mechanisms.	Reduces the need for testing every strengthening layout and supports parametric evaluation.	Reliability depends on material models, bond assumptions, calibration quality, and validation against experiments.

In general, strengthening and repair studies show that the capacity of deficient or damaged RCCs can be improved, but the strengthened system may behave differently from an original unstrengthened corbel. The main gains are usually related to higher ultimate load, delayed crack initiation, reduced crack width, and improved stiffness. However, the main concerns are premature debonding, brittle failure, limited ductility, and sensitivity to anchorage detailing. Therefore, strengthening studies should be treated separately from the main database of original RCCs behavior. They are valuable for rehabilitation practice and for identifying future research needs, but they should not be mixed directly with unstrengthened specimens when developing or validating shear-capacity models.

As a conclusion, the reviewed strengthening and repair studies demonstrate that deficient or damaged RCCs can be upgraded using several techniques. However, the effectiveness of each method depends on the strengthening configuration, anchorage condition, bond quality, concrete condition, and governing failure mode. Table 9 summarizes the main strengthening and repair approaches reported in the reviewed literature and identifies their typical advantages and limitations.

The findings indicate that strengthening and repair techniques can improve the capacity and serviceability of RCCs, but they may also change the governing failure mechanism. Therefore, strengthened or repaired specimens should be classified separately from original unstrengthened specimens when developing experimental databases or ML-based shear-capacity models.

6. Systematic Review of Analytical and Code-Based Models

RCCs are discontinuity regions (D-regions) with nonlinear strain behavior governed mainly by shear [44], [95]. Therefore, several analytical and code-based models have been adopted by international design provisions to estimate the ultimate capacity of corbels [131], [132]. In this section, a comparison is presented among four analytical methods adopted by three selected international building codes [133]. These provisions include ACI 318-25 [27], which employs two methods: the Shear Friction Method and the Strut-and-Tie Method; BS EN 1992-1-1:2004 [134], which adopts a Simplified Strut-and-Tie Model; and GB 50010-2010 [11], which applies a Triangular Truss Analogy Model, as follows:

6.1 ACI 318 Shear Friction Method

The shear friction method as per the ACI 318-25 [27] code includes a simplified design procedure for corbels with an a_v/d ratio of unity or less, subjected to both vertical and horizontal loads. This procedure is based on a simple mechanical model, often referred to as the flexural model, which has been adopted by the ACI 318-25 code [27].

The ultimate shear stress (v_u) should not exceed the limits specified in Eq. (1):

$$v_u \leq \min(0.2f'_c, 5.5 \text{ MPa}) \quad (1)$$

The area of reinforcement crossing the shear plane, A_{vf} , is determined using Eq. (2):

$$A_{vf} = \frac{V_u}{0.75f_{yf} \cdot \mu} \quad (2)$$

Where $\mu = 1.4$ for corbels cast monolithically with the column.

The ultimate moment M_u , which the corbel-column interface must resist, is calculated using Eq. (3):

$$M_u = V_u \cdot a_v + N_u \cdot (h - d) \quad (3)$$

The area of reinforcement, A_f , required to resist the ultimate moment is found by Eq. (4):

$$A_f = \frac{M_u}{\phi \cdot f_{yf} \cdot \left(d - \frac{a}{2}\right)} \quad (4)$$

The area of reinforcement, A_n , required to resist the horizontal force N_u is given by Eq. (5):

$$A_n = \frac{N_u}{0.75 f_{yf}} \quad (5)$$

The main reinforcement area, A_s , is determined by taking the greater value of Eq. (6):

$$A_s = \max\left(A_f + A_n, \frac{2}{3} A_{vf} + A_n\right) \quad (6)$$

Closed stirrups, with an area A_h , parallel to the main tension reinforcement A_s , should be uniformly distributed within two-thirds of the effective depth and calculated by Eq. (7):

$$A_h \geq 0.5(A_s - A_n) \quad (7)$$

Lastly, the steel ratio ρ should not be less than the value of Eq. (8):

$$\rho = \frac{A_s}{b \cdot d} \geq 0.04 \cdot \frac{f'_c}{f_{yf}} \quad (8)$$

6.2 ACI 318 Strut-and-Tie Model

As outlined in ACI 318-25, the STM is applicable for corbels with a shear a/d ratio not exceeding 2. This model assumes a structural composition primarily of steel reinforcement. Initially, an STM is devised based on the principle of minimum strain energy [135]. The model chosen forms a truss system comprising diagonal concrete compression struts and longitudinal reinforcement.

As depicted in Fig. 15, the STM includes CCC (three-sided compression) nodal zones B and B', CCT (a combination of two-sided compression and one-sided tension) nodal zones A and A', concrete compression struts AB and A'B', and steel ties AA'. The width of the CCT nodal region corresponds to the width of the supporting plate, while the height is twice the distance from the concrete edge to the longitudinal reinforcement's center. For the CCC nodal region, the width is half the column width [136], and the height represents the equivalent height of the compression zone, symbolized as β_{1c} .

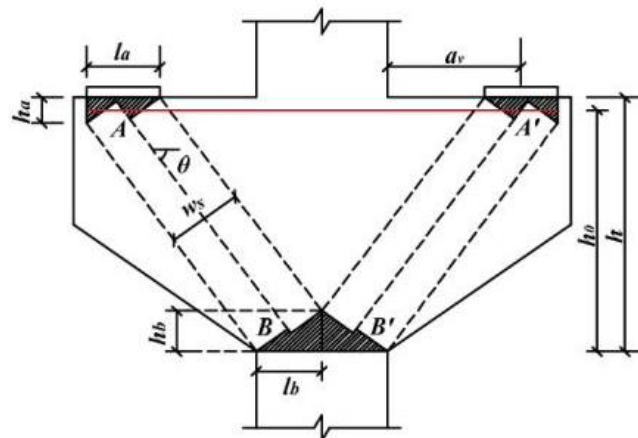


Fig. 15. Strut and tie model for symmetrical two-sided corbel [67]

The STM simplifies complex stress distributions into uniaxial force elements comprising compression struts, tensile ties, and nodal regions [137]-[141]. These components together withstand the external loads. The code mandates strength checks for each element, ensuring that when any element reaches its full capacity, the member attains its maximum value (V_u). Furthermore, the STM adheres to the principles of static equilibrium and material yield conditions,

ensuring all nodes satisfy equilibrium equations and stress levels in each element remain below yield stress. Theoretically, the STM is subject to a lower-bound theorem of limit analysis.

The angle θ and the strut width w_s of the compression strut are determined using the following formulas:

$$\tan \theta = \frac{\left(h_0 - \frac{h_b}{2}\right)}{\left(a_v + \frac{l_b}{2}\right)} \quad (9)$$

$$w_s = \text{Min of } (h_a \cos \theta + l_a \sin \theta, h_b \cos \theta + l_b \sin \theta) \quad (10)$$

The load limit of each model component was calculated. By applying static equilibrium conditions, the ultimate shear strength of the corbel was determined at the point where each component reached its ultimate strength. The lowest computed value was selected as the shear strength of the corbel, referred to as V_u . The formulas for each component are as follows:

$$V_{u,AB} = F_{u,AB} \sin \theta = f_{ce,s} w_s b \sin \theta \quad (11)$$

$$V_{u,AA'} = F_{u,AA'} \tan \theta = f_{yf} A_s \tan \theta \quad (12)$$

For the bearing capacity calculations at Node A, $V_{u,NodeA}$ is taken as the minimum of the three expressions given in Eq. (13):

$$\begin{aligned} V_{u,ba} &= F_{u,ba} \tan \theta = f_{ce,n} h_a b \tan \theta \\ V_{u,inc} &= F_{u,inc} \sin \theta = f_{ce,n} (h_a \cos \theta + l_a \sin \theta) b \sin \theta \\ V_{u,be} &= F_{u,be} = f_{ce,n} l_a b \end{aligned} \quad (13)$$

Similarly, $V_{u,NodeB}$ is taken as the minimum of the three expressions given in Eq. (14):

$$\begin{aligned} V_{u,ba} &= F_{u,ba} \tan \theta = f_{ce,n} h_b b \tan \theta \\ V_{u,inc} &= F_{u,inc} \sin \theta = f_{ce,n} (h_b \cos \theta + l_b \sin \theta) b \sin \theta \\ V_{u,be} &= F_{u,be} = f_{ce,n} l_b b \end{aligned} \quad (14)$$

The values of $f_{ce,s}$ and $f_{ce,n}$ are calculated as:

$$f_{ce,s} = 0.85 \beta_c \beta_s f_c' \quad (15)$$

$$f_{ce,n} = 0.85 \beta_n f_c' \quad (16)$$

$$h_b = \beta_1 c = \frac{f_{yf} A_s}{0.85 f_c' b} \quad (17)$$

Finally, the shear strength of the corbel V_u is given by the minimum of the individual capacities:

$$V_u = \text{Min of } (V_{u,AB}, V_{u,AA'}, V_{u,NodeA}, V_{u,NodeB}) \quad (18)$$

In the given formulas, $F_{u,AB}$, $F_{u,AA'}$, $F_{u,ba}$, $F_{u,be}$, and $F_{u,inc}$ denote the maximum loads that various structural elements can withstand. Specifically, $F_{u,AB}$ represents the load capacity of the compression struts, $F_{u,AA'}$ for the tension ties, $F_{u,ba}$ for compression struts in the nodal area or surfaces normal to horizontal stirrups, $F_{u,be}$ for concentrated loads in the nodal zone or surfaces normal to vertical compression struts, and $F_{u,inc}$ for surfaces normal to inclined compression struts in the nodal zone. Correspondingly, $V_{u,AB}$, $V_{u,AA'}$, $V_{u,NodeA}$, and $V_{u,NodeB}$ refer to the corbel bearing capacities when each of these components reaches their ultimate strength. The formulas also define $f_{ce,s}$ and $f_{ce,n}$ as the maximum allowable compressive stresses for the concrete in the struts and the nodal zones, respectively.

The confinement factor, β_c , for the strut and node is determined as the smaller value between $\sqrt{A_2/A_1}$ and 2. Here, A_1 represents the bearing area, while A_2 corresponds to the area of the lower base of the largest frustum of a tapered wedge, which is entirely contained within the support and has an upper base equal to the loaded area. For corbel elements, β_c equals 1. The strut coefficient, β_s , is used to adjust for confinement conditions. It is set at 0.75 for interior struts with an orthogonal reinforcement grid having a minimum distributed ratio of 0.0025 in each direction, or with reinforcement in one direction crossing the strut at angle α_1 of $0.0025/\sin^2\alpha_1$, provided that α_1 shall not be less than 40° . Otherwise, β_s is set at 0.4.

Similarly, the nodal zone coefficient, β_n , is taken as 1.0 for the node "B" under three-sided compression, and 0.8 for the node "A" with a single tension tie passing through. Lastly, when calculating the concrete compression strut elements, the current design codes STM does not specifically account for the impact of diagonal cracks on the struts. Instead, the design employs a simplified strut coefficient related to the strut efficiency.

6.3 BS EN 1992-1-1:2004 Strut-and-Tie Model

Eurocode 2 specifically permits the application of the strut-and-tie method for the analysis and design of corbels. According to clause 6.5.1 of EN 1992-1-1:2004 [134], this method is suitable for conditions involving nonlinear stress distribution, such as near supports, under concentrated loads, or in regions subjected to combined stress. RCCs can be designed employing the STM to address the nonlinear stress distributions near supports or concentrated loads. In this model, the corbel is conceptualized with an inclined concrete strut and a horizontal steel tie. The geometry and forces are depicted in Fig. 16.

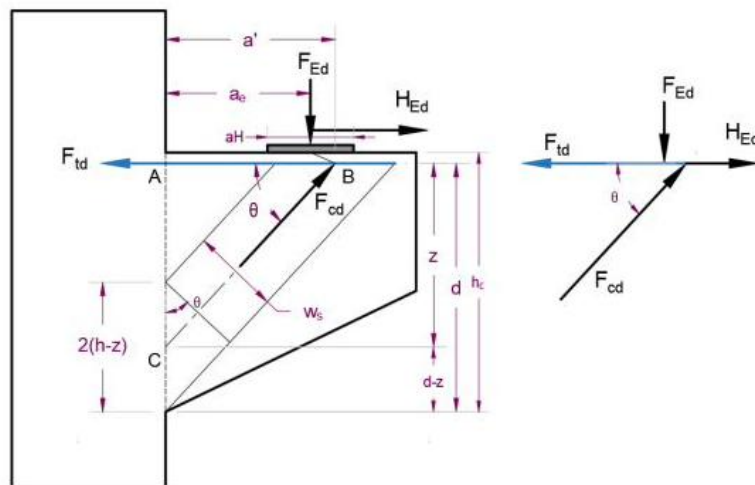


Fig. 16. Strut and tie analysis of a corbel as per Eurocode 2 [134]

The lever arm (z) is determined by the equation:

$$z = a' \tan \theta \quad (19)$$

$$a' = a_e + 0.2a_H \quad (20)$$

Where a_e is the distance from the column face to the load application point, a_H is the width of the bearing plate, and θ is the inclination angle of the strut.

The force in the concrete strut, F_{cd} , is calculated as:

$$F_{cd} = f_{cd} \times W_{strut} \times b_w \quad (21)$$

In which, $f_{cd} = 0.34f_{ck} \times \left(1 - \frac{f_{ck}}{250}\right)$ is the design compressive stress of the concrete strut; $W_{strut} = 2(d - z) \cos \theta$ is the width of the strut perpendicular to its axis, and b_w is the width of the corbel.

The inclination angle θ ($45^\circ \leq \theta \leq 68^\circ$) is determined by the equation:

$$\frac{F_{Ed}}{f_{cd}db_w} = \left(1 - \frac{a'}{d} \tan \theta\right) \sin 2\theta \quad (22)$$

This equation may require iterative methods or design charts to solve for θ .

Resolving horizontally at B, the force F_{td} in the steel tie is:

$$F_{td} = F_{Ed} \cot \theta \quad (23)$$

Therefore, the total force F'_{td} in the steel tie, accounting for the horizontal force of $0.2F_{Ed}$, is:

$$F'_{td} = F_{Ed} \cot \theta + 0.2F_{Ed} \quad (24)$$

Thus, the area of main tension steel, $A_{s,main}$, is calculated as:

$$A_{s,main} = \frac{F'_{td}}{0.87f_{yk}} \quad (25)$$

Moreover, closed horizontal links are provided only if $a_e/h_c \leq 0.5$, and the total area of both legs of a link, $A_{s,link}$, is given by:

$$A_{s,link} \geq 0.5A_{s,main} \quad (26)$$

6.4 GB 50010-2010 Triangular Truss Model

In accordance with the Chinese standard GB 50010-2010 [11], short corbels with an a/d ratio of less than 1 are analysed using a triangular truss model [142]. This model assumes that the horizontal longitudinal reinforcement at the top of the corbel acts as a tension tie, while the concrete in the diagonal region functions as a compression strut. Reference is made to Fig. 17, and evaluating the moment equilibrium at point A, the following equation is derived:

$$f_{yf}A_s h_1 = F_v a_v + F_h (h_1 + a_s) \quad (27)$$

Where F_v and F_h represent vertical and horizontal design loads, respectively; f_y and A_s denote the yield strength and area of the longitudinal reinforcement; h_1 is the internal lever arm, approximately $0.85h_0$ with h_0 being the effective depth; $(h_1 + a_s)$ adjusts the moment arm, in which

a_s is the lever arm of the shear span; and a_v is the shear span length, set to $0.3h_0$ if it is less than this value. To ensure adequate reinforcement, the total cross-sectional area must satisfy:

$$A_s \geq \frac{F_v a_v}{0.85 f_{yf} h_0} + \frac{1.2 F_h}{f_{yf}} \quad (28)$$

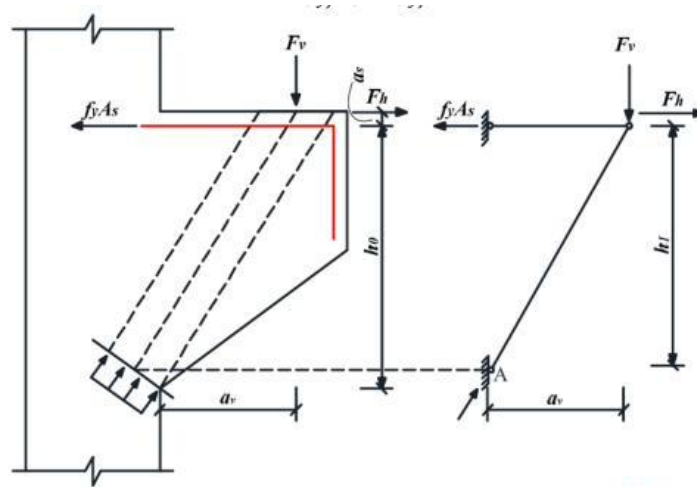


Fig. 17. Triangular truss model as per GB 50010-2010 code [67]

Table 10. Summary of reviewed analytical and code-based models for RCCs

Model / code provision	Main mechanical assumption	Applicability	Main advantages	Main limitations
ACI 318 shear-friction method [9], [27]	Shear transfer occurs along a potential shear plane at the corbel-column interface through reinforcement crossing the plane and concrete friction.	Mainly short corbels with $a_v/d \leq 1.0$, subjected to vertical load with or without horizontal force.	Simple design format, direct calculation of required reinforcement, and practical use in routine design.	May not fully represent diagonal strut action, nodal crushing, bearing effects, or complex reinforcement interaction.
ACI 318 strut-and-tie method [9], [27]	The corbel is idealized as a truss system consisting of concrete compression struts, steel tension ties, and nodal zones.	D-regions and corbels where nonlinear strain distribution controls behavior.	Mechanically meaningful, suitable for disturbed regions, and consistent with internal force equilibrium.	Requires assumed strut-and-tie geometry; prediction depends on strut efficiency factors, nodal strength, and detailing assumptions.
BS EN 1992-1-1:2004 strut-and-tie model [10]	Load is transferred through an inclined concrete strut and a horizontal steel tie.	Corbels and regions near supports or concentrated loads where stress distribution is nonlinear.	Provides a rational design framework for concentrated-load regions and includes limits on strut inclination.	May require iterative solution for strut angle and depends on selected stress limits and geometric idealization.
GB 50010-2010 triangular truss model [11]	The top longitudinal reinforcement acts as a tension tie, while the diagonal concrete zone acts as a compression strut.	Short corbels, generally with $a/d < 1.0$.	Simple equilibrium-based method and easy to apply in design calculations.	Does not explicitly capture all possible failure modes, such as concrete crushing due to bending, local bearing distress, or detailed crack development.

When only a vertical load is applied, the bearing capacity is calculated using:

$$F_v \leq 0.85 \frac{f_{yf} A_s h_0}{a_v} \quad (29)$$

Additionally, to control cracking, the corbel dimensions must meet:

$$F_v \leq \beta \left(1 - \frac{0.5 F_{hk}}{F_{vk}} \right) \frac{f_{tk} b h_0}{0.5 + \frac{a_v}{h_0}} \quad (30)$$

Where F_{vk} and F_{hk} are the standard vertical and horizontal loads, respectively, taken as $0.67 F_v$ and $0.67 F_h$; f_{tk} is the standard tensile strength of the concrete; b is the corbel width; and β is the crack control coefficient, set to 0.65 for corbels supporting crane beams and 0.80 for other corbels. The bearing capacity is assessed using a simplified triangular truss model, which does not account for concrete crushing due to bending.

As a summary, the reviewed design approaches show that current code-based models provide practical procedures for RCCs design, but each method is based on different mechanical assumptions and applicability limits. The shear-friction method is simple and suitable for short corbels, while the strut-and-tie method provides a more rational representation of the internal load path in D-regions. The triangular-truss approach also gives a simplified equilibrium-based representation of the corbel mechanism. However, the accuracy of these methods depends on the assumed failure mechanism, reinforcement detailing, concrete strength, bearing condition, and the treatment of horizontal force. Table 10 summarizes the main characteristics of the reviewed analytical and code-based models.

The comparison indicates that no single code-based approach can fully represent all aspects of RCCs behavior. Therefore, code predictions should be interpreted together with experimental evidence, parameter studies, and mechanics-based understanding. This also supports the need for explainable data-driven interpretation, where ML tools are used to identify database trends without replacing established design provisions.

6.5 Limitations of Existing Design and Prediction Approaches

Bringing together the evidence of Sections 4 to 6, the limitations of the current design and prediction approaches can be grouped into five categories, each of which suggests a specific research response. The first limitation is incomplete representation of the interacting variables. The shear-friction formulation of Eqs (1) to (8) resolves the problem into reinforcement crossing an assumed shear plane and therefore does not carry the strut inclination, the nodal geometry, or the bearing dimensions explicitly, while the triangular-truss formulation of Eqs (27) to (30) is an equilibrium statement that does not address concrete crushing in bending or local bearing distress. The consequence is visible in the experimental comparisons: Abdul-Razzaq and Dawood [43] reported that the deviation of the shear-friction and strut-and-tie predictions from the measured failure load grew from 15% and 22% at $a/d = 0.5$ to 32% and 37% at $a/d = 1.5$, so the error is not a fixed safety margin but a function of the geometry. The corresponding research need is a systematic reassessment of the strut efficiency and nodal strength factors against a modern database stratified by a/d , rather than a single calibration applied across the whole range.

The second limitation concerns the assumed failure mechanism. Each method is anchored to one mechanism, whereas the reviewed tests show that the governing mode migrates with a/d , reinforcement detailing, concrete strength, and loading history, as discussed in Section 4. A method calibrated on sliding-type behavior is therefore applied outside its mechanical basis when the specimen fails by nodal crushing or by flexural yielding of the tie. Future work should aim at mechanism-aware provisions, in which the applicable expression is selected by an explicit criterion rather than by a single geometric threshold.

The third limitation is the narrowness of the calibration base relative to current practice. The provisions were established largely on monotonic tests of conventional normal-strength corbels, yet a substantial part of the recent literature concerns high-strength, fibre-reinforced, recycled-

aggregate, UHPC, SCC, and FRP-reinforced members, and Section 3.1 shows that this material is where the growth of the field is concentrated. Extending and harmonizing the experimental database, with consistent reporting of geometry, reinforcement, bearing arrangement, and failure mode, is a prerequisite for any recalibration.

The fourth limitation applies to the data-driven models that have been proposed as alternatives. As Section 7.2 discusses, high statistical accuracy inside the training range does not establish safe extrapolation, and models such as CatBoost or a conventional ANN provide no mechanical account of their own predictions. The productive direction here is the one represented by the SR-STM approach of Megahed [144] and by the SHAP interpretation adopted in the present study, namely models that either retain the mechanical form or expose the contribution of each variable, together with an explicit statement of the parameter ranges within which they may be used.

The fifth limitation is that both code and data-driven approaches are almost entirely deterministic and address ultimate capacity alone. Neither the scatter of the predictions nor the serviceability quantities that often govern in practice, such as crack width at the corbel-column junction under sustained or repeated service load, are treated formally. Probabilistic formulations of the kind proposed by Nguyen et al. [143], combined with reliability-based calibration and with explicit serviceability criteria, would allow the observed scatter to be carried into design rather than absorbed silently by a global safety factor. Taken together, these five directions define a coherent programme: a broader and better-reported database, mechanism-aware and geometry-sensitive strength provisions, interpretable data-driven models with stated applicability limits, and a probabilistic treatment covering both ultimate and serviceability limit states.

7. ML-Based Prediction of RCCs Shear Capacity

The reviewed analytical and code-based models provide practical procedures for estimating the shear capacity of RCCs. However, these models are generally based on simplified assumptions regarding the internal load-transfer mechanism, reinforcement contribution, strut efficiency, and nodal strength. As discussed in Section 6, the code-adopted approaches are useful for design, but they do not fully capture the nonlinear interaction among geometry, concrete strength, reinforcement ratios, reinforcement yield strength, and loading configuration. This limitation becomes more evident when experimental databases include wide variations in specimen dimensions, material properties, and reinforcement details.

ML models have recently become an important direction in predicting the shear capacity of RCCs [143]. This interest is mainly due to the nonlinear nature of corbel behavior. Traditional design models remain useful because they are simple and mechanically meaningful; however, their prediction accuracy may be affected by the limited number of variables included in their formulations. In contrast, ML models can learn complex relationships from experimental databases, provided that the database is carefully compiled, consistently defined, and limited to compatible test conditions.

In this study, the ML component is used as an interpretation tool rather than as a replacement for design-code provisions. To achieve this, the ML dataset was restricted to compatible vertical-load specimens and excluded direct horizontal-force cases, strengthened or repaired specimens, and specimens made with special materials. This boundary was adopted to ensure that the model interprets the shear behavior of original RCCs governed mainly by vertical-load transfer. The following subsections first summarize the available ML studies on RCC shear prediction, then present the XGBoost model used in this study, and finally discuss the SHAP-based interpretation of the governing input variables.

7.1 Summary of Published ML Studies

The available ML-based studies on RCCs shear capacity remain limited compared with the wider literature on RC beams and deep beams. Most published work relies on artificial neural networks or hybrid ML models. Table 11 summarizes the main ML studies directly relevant to RCCs shear-capacity prediction. Abbas and Ali (2025) presented one of the most direct ANN applications for RCCs. Their model used 330 experimentally tested specimens and 13 input variables, and the best

BPNN architecture was 13-10-9-1 with a Pearson correlation coefficient of 0.990. The same study compared ANN predictions with ACI 318-19, EN 1992-1-1, and GB 50010-2010 methods, showing that ANN predictions were more consistent than the examined code-based equations [13]. The same data-driven treatment was subsequently extended to corbels in which a horizontal tension force acts together with the vertical load [145]. That loading condition is outside the scope of the database compiled in the present study.

Table 11. Summary of ML studies on RCCs shear capacity

Study	Dataset size	Model used	Input variables	Output	Main performance	Main limitation
Kumar and Barai (2010) [91]	Experimental data for steel-fibre RCCs without shear reinforcement	Artificial neural network	Concrete strength, fibre content, flexural reinforcement, shear span/depth-related parameters	Ultimate shear capacity	Strong agreement with experimental results, with MAE = 0.070, RMSE = 0.098, and R = 0.97	Focused on steel-fibre RCCs without shear reinforcement; limited generality for conventional RCCs
Megahed (2024) [144]	371 RCCs tests, with 810 RC deep-beam tests also used in the broader study	STM-based symbolic regression, SR-STM, and CatBoost benchmark	Geometry, concrete strength, longitudinal reinforcement, vertical and horizontal web reinforcement, loading plate/column dimensions, and STM-related variables	Shear strength index / shear strength	For RCCs, SR-STM achieved mean prediction-to-actual ratio = 1.004, R ² = 0.862, CoV = 14.95%; CatBoost gave higher accuracy with CoV = 7.19%	SR-STM is more interpretable than CatBoost, but its validity is limited to the database range; CatBoost remains black-box in nature
Abbas and Ali (2025) [13]	330 RCCs specimens	Backpropagation neural network, BPNN	13 input variables: square root of f_c' , shear span, width, column width, effective depth, height, a/d , longitudinal reinforcement ratio, horizontal and vertical reinforcement ratios, and steel yield strengths	Experimental shear strength	Best architecture 13-10-9-1; Pearson R = 0.990; code methods had lower R values of 0.901-0.927	Data-driven model; applicability limited to the parameter ranges of the collected database

Megahed (2024) introduced a different and more interpretable ML direction by combining symbolic regression with the strut-and-tie model. The study used a large database of 810 RC deep beams and 371 RCCs and developed an STM-based symbolic regression model. Unlike purely black-box ML models, the SR-STM approach produced explicit mathematical expressions linked to the diagonal strut and truss mechanisms. For RCCs, the SR-STM model achieved a mean prediction-to-actual ratio of 1.004, R^2 of 0.862, and CoV of 14.95%, while CatBoost showed stronger accuracy but less interpretability [144].

7.2 Critical Assessment of Existing ML Models

The reviewed ML studies show that data-driven models can improve prediction accuracy compared with many traditional code equations. However, the available ML literature on RCCs is still relatively narrow. The most common approach is ANN-based prediction, while other algorithms

such as Random Forest, XGBoost, Gaussian Process Regression, Support Vector Regression, and explainable ensemble models have not yet been explored sufficiently for RCCs.

A main limitation is that high statistical accuracy does not always mean safe generalization. ANN and CatBoost models can perform very well within the range of the training database, but their predictions may become unreliable when applied to corbels with unusual geometry, reinforcement details, concrete strength, or loading conditions. This issue was clearly noted by Abbas and Ali (2025), who limited the use of their ANN model to the parameter ranges covered by the experimental database [13].

Another limitation is interpretability. Black-box models can give accurate predictions, but they do not always explain why a certain capacity is predicted. This is important in structural engineering because designers need both accuracy and mechanical meaning. Megahed (2024) addressed this issue by developing an SR-STM model that keeps the mechanical logic of the strut-and-tie method while using symbolic regression to improve prediction accuracy. This makes the model easier to interpret than CatBoost or a conventional ANN [144].

The work of Megahed [144] also shows the value of explainability tools. Its SHAP analysis indicated that the shear span-to-depth ratio and effective longitudinal reinforcement ratio were among the most influential variables for RCCs shear-strength prediction. This agrees with the physical understanding of corbel behavior, where the compression strut angle, tie reinforcement, and reinforcement effectiveness strongly control the load-transfer mechanism.

7.3 ML Model Used for SHAP Interpretation

In the present study, the ML component was not introduced to propose a new benchmark design equation for RCCs shear-capacity prediction. Several previous studies have already reported accurate data-driven models for RCCs, including ANN-based and symbolic-regression-based approaches. Therefore, the purpose of the present modelling step was more focused: to provide an interpretable data-driven framework that can explain how the main geometric, material, and reinforcement-related variables influence the predicted shear capacity of RCCs.

To achieve this, an Extreme Gradient Boosting (XGBoost) ensemble regressor was trained using a compiled database of 330 experimentally tested RCCs. The model included 13 input variables: square root of concrete compressive strength, shear span, corbel width, column width, effective depth, corbel height, shear span-to-effective depth ratio, flexural reinforcement ratio, horizontal reinforcement ratio, vertical reinforcement ratio, transverse steel yield strength, horizontal steel yield strength, and vertical steel yield strength. The target variable was the experimental shear capacity, V_{exp} . All input variables and the target variable were scaled to the range [0,1] using min-max normalization before model training. The normalized V_{exp} values had a mean of 0.1608 and a standard deviation of 0.1271.

The database was randomly divided into training and testing subsets using an 80:20 split ratio. Accordingly, 264 specimens were used for training, while 66 specimens were used for testing. A fixed random seed of 42 was adopted to ensure reproducibility. The XGBoost model was configured with 300 estimators, a maximum tree depth of 6, a learning rate of 0.05, a subsample ratio of 0.8, and a column-sampling ratio of 0.8. The model was trained using all available CPU cores. These parameters were selected to provide a balance between predictive accuracy and model stability.

As shown in Fig. 18, the model achieved a coefficient of determination, R^2 , of 0.9973 for the training set and 0.9090 for the testing set. The corresponding RMSE values were 0.0066 and 0.0388, respectively. These results indicate very close fitting for the training data and good predictive performance for the testing data. However, the difference between training and testing performance also indicates that the model should be interpreted with care and should not be presented as a new design equation. In this study, the XGBoost model was considered sufficient for SHAP-based interpretation, rather than for claiming superiority over existing ANN or code-based models.

This gap between the training and testing coefficients of determination, 0.9973 against 0.9090, should be stated explicitly as a mild overfitting of the model and is acknowledged here as a

limitation of the present modelling step rather than as an incidental observation. Three regularization measures were in fact embedded in the configuration described above. The learning rate was held at 0.05, which is deliberately low and requires the ensemble to accumulate the fit gradually over 300 trees instead of committing to large corrections early. The maximum tree depth was capped at 6, which limits the order of interaction any single tree can represent and prevents individual branches from isolating small groups of specimens. Stochastic sampling was applied on both axes, with a subsample ratio of 0.8 for the training rows and a column-sampling ratio of 0.8 for the features, so that each tree is fitted to a different perturbation of the data and the ensemble is decorrelated. These three measures together constrain the model, but they do not remove the residual gap, and the reason is a property of the dataset rather than of the algorithm: 264 training specimens are a small sample for a 13-dimensional input space, and gradient-boosted trees will continue to fit residual structure in such a sample even under moderate constraint. Additional shrinkage through the L1 and L2 penalty terms, early stopping monitored on a validation fold, and k -fold cross-validation in place of a single fixed 80:20 split with seed 42 would narrow the gap further and would also provide a variance estimate for the reported metrics; these steps were not applied here because the objective was interpretation rather than benchmarking, and because the SHAP attributions are computed on the fitted model and are therefore conditional on it. The practical consequence must be stated plainly. The testing R^2 of 0.9090 is the honest indicator of predictive performance, the training value of 0.9973 is not, and the model is offered strictly as an explanatory instrument for the trends within the compiled database. It is not proposed as a design equation, and its output should not be extrapolated beyond the parameter ranges of the 330 specimens on which it was trained. This limitation is restated in Section 9. A k -fold cross-validated procedure of this type has been applied to shear-strength prediction in RC deep beams [146], which are discontinuity regions like corbels, and it is the appropriate next step for the present model should it be developed beyond an interpretive role.

SHAP analysis was then conducted using the TreeExplainer algorithm. SHAP values were computed for the full dataset of 330 specimens, producing a SHAP matrix with a size of 330×13 . The model base value, $E[f(X)]$, was 0.1580. Accordingly, the XGBoost model was adopted as an explanatory tool to support the interpretation of database trends. This approach helps reduce the black-box nature of ML methods and allows the model output to be discussed in relation to the known mechanical behavior of RCCs.

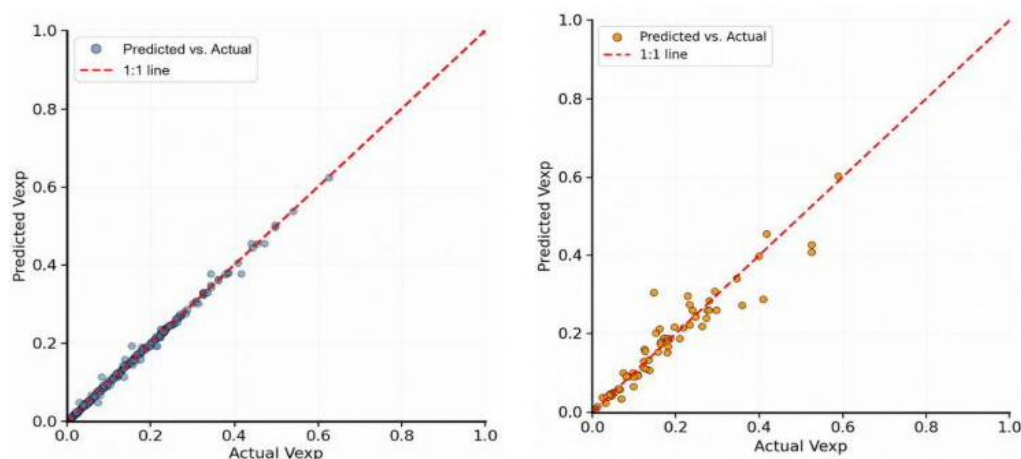


Fig. 18. Actual vs. predicted normalized experimental shear capacity for the XGBoost model: (a) training set and (b) testing set

7.4 SHAP-Based Interpretation of Input Variables

To interpret the influence of the input parameters on the predicted shear capacity, SHAP (SHapley Additive exPlanations) analysis was carried out using the trained XGBoost model. SHAP values quantify the contribution of each input variable to the predicted output. Positive SHAP values push the prediction above the model base value, while negative values reduce the prediction below that

value. In this way, SHAP analysis provides both global and local interpretation of the model behavior.

In the present work, SHAP analysis was not used as a replacement for design-code assessment. Rather, it was used to explain the relative importance and direction of the main variables that control the predicted shear capacity. This is especially useful because the behavior of RCCs is governed by interaction between geometry, concrete strength, reinforcement, and the load-transfer mechanism.

7.4.1 Global Importance of Variables

The global SHAP feature-importance plot is presented in Fig. 19, while the numerical ranking is summarized in Table 12. The results show that the most influential variables were corbel height, h , corbel width, b , and column width, w_c . These were followed by the shear span-to-effective depth ratio, a/d , and the square root of concrete compressive strength, $(f_{ck})^{0.5}$. Other variables with moderate influence included the effective depth, d , and the flexural reinforcement ratio, ρ_f . The horizontal reinforcement ratio, ρ_h , and the yield strengths of reinforcement had smaller effects, while the vertical reinforcement ratio, ρ_v , and vertical steel yield strength, f_{yv} , had the lowest SHAP importance within the present database.

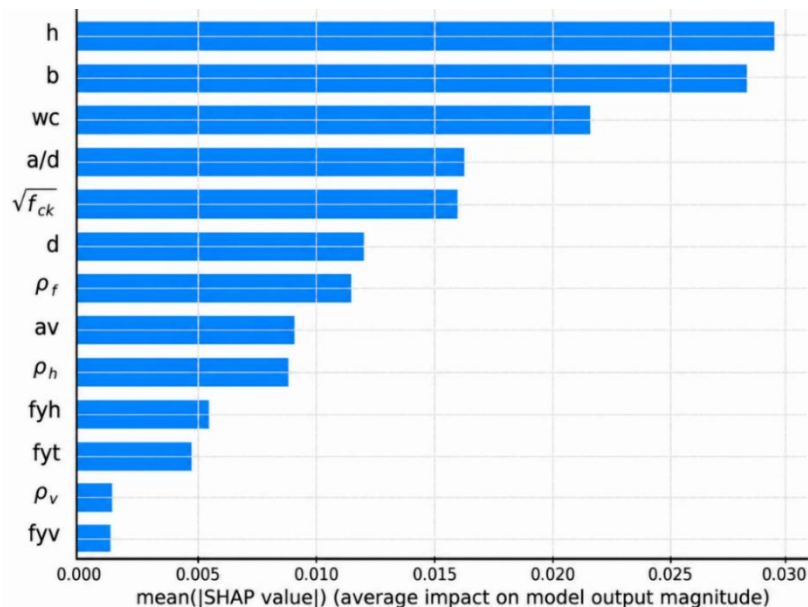


Fig. 19. SHAP feature importance based on mean absolute SHAP value

Table 12. SHAP ranking and physical interpretation of input variables

Rank	Feature	Mean SHAP	Effect direction	Interpretation
1	h	0.0296	Positive	Larger height increases the predicted shear capacity.
2	b	0.0284	Positive	Wider corbels provide larger bearing area and higher predicted capacity.
3	w_c	0.0217	Positive	Larger column/support width improves the load-transfer zone.
4	a/d	0.0163	Negative	Increasing a/d reduces the predicted shear capacity.
5	$(f_{ck})^{0.5}$	0.0161	Positive	Higher concrete strength increases the capacity of the compression strut.
6	d	0.0121	Positive	Greater effective depth has a moderate positive effect.
7	ρ_f	0.0116	Positive	Flexural steel supports the tension-tie mechanism.
8	av	0.0092	Negative	Larger shear span tends to reduce capacity.

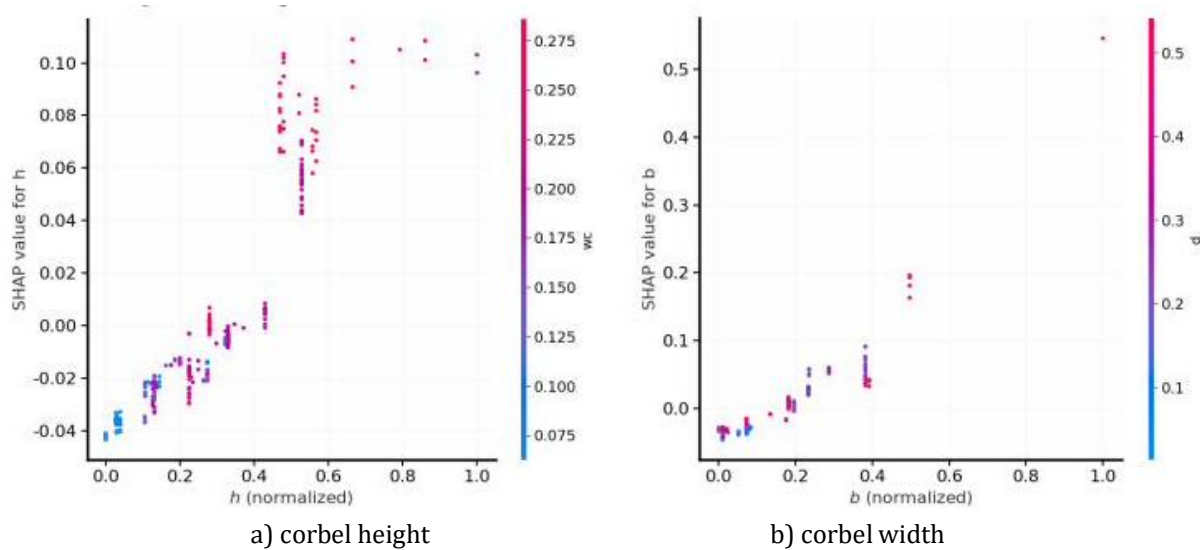
Rank	Feature	Mean SHAP	Effect direction	Interpretation
9	rho_h	0.0089	Positive	Horizontal reinforcement gives a smaller positive contribution.
10	fyh	0.0055	Positive	Horizontal steel yield strength has low importance in this data.
11	fyt	0.0048	Positive	Transverse steel yield strength has low importance.
12	rho_v	0.0015	Positive	Vertical rebar ratio shows a very small global contribution.
13	fyv	0.0014	Positive	Vertical steel yield strength is the least influential variable in the model.

The high ranking of dimensional variables is structurally reasonable because the model output is shearing capacity rather than a fully normalized shear stress. Larger corbel dimensions increase the area available for stress transfer, enlarge the compression field, and improve the load-carrying path. At the same time, the importance of a/d confirms that the model captured the central role of strut geometry in RCCs behavior.

7.4.2 Effect of Geometric Variables

The SHAP dependence plots for the main geometric variables, including corbel height, h , corbel width, b , and column width, w_c , are presented in Fig. 20. The dependence plots show that these variables generally had positive SHAP contributions. In practical terms, this means that increasing these dimensions tends to push the predicted shear capacity upward. This agrees with the mechanics of corbel action because larger dimensions increase the size of the compression strut, improve the bearing region, and provide a larger area for stress redistribution.

The strong influence of h and b also indicates that the model learned the importance of member size. This is expected because the experimental output is expressed as normalized capacity, and not only as a dimensionless shear-strength index. Therefore, the high SHAP ranking of h and b should be interpreted as a combined size effect and mechanical effect. It confirms that the available load-transfer area is one of the dominant contributors to predicted corbel capacity within the range of the compiled database.



7.4.3 Effect of Shear Span-To-Effective Depth Ratio

The shear span-to-effective depth ratio, a/d , showed a clear negative effect on the predicted shear capacity. As shown in Fig. 21, small values of a/d were associated with positive SHAP values,

meaning that short shear spans increased the predicted capacity above the model base value. As a/d increased, the SHAP values decreased and became negative. This indicates that larger shear span ratios reduce the predicted capacity.

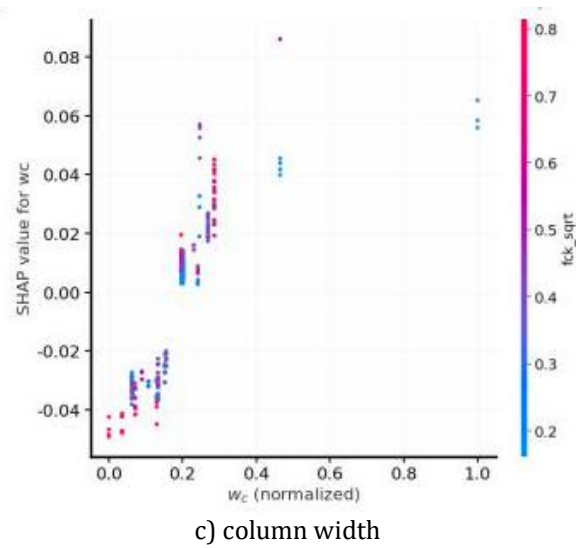


Fig. 20. SHAP dependence plots for the main dimensional geometric variables

This trend is one of the most important findings of the SHAP analysis because it agrees directly with the physical behavior of RCCs. When a/d is small, the applied load is transferred more directly to the support through a steep diagonal compression strut. This direct strut action increases the shear capacity. When a/d increases, the strut becomes less direct, flexural effects become more significant, and the predicted shear resistance decreases. The SHAP interaction coloring also indicates that the influence of a/d is linked with the shear span, a_v , and the effective depth, d , which is consistent with the geometric definition of the load path.

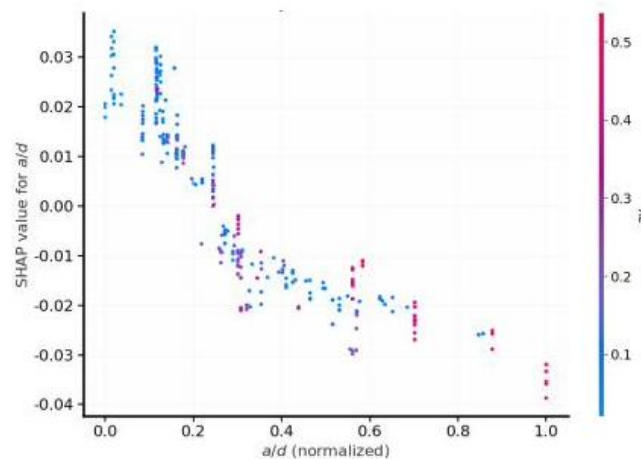


Fig. 21. Detailed SHAP plot for the shear span-to-effective depth ratio

7.4.4 Effect of Concrete Compressive Strength

The SHAP dependence plot for the square root of concrete compressive strength, $(f_{ck})^{0.5}$, is presented in Fig. 22. The plot shows a generally positive monotonic trend. At lower concrete-strength values, the SHAP contribution was mostly negative, indicating a reduction in the predicted capacity relative to the model base value. At higher values, the SHAP contribution became positive and increased noticeably.

This finding is mechanically meaningful because the shear capacity of RCCs depends strongly on the strength and integrity of the concrete compression strut. Higher concrete strength improves resistance to local crushing, diagonal compression, and bearing stresses. The use of $(f_{ck})^{0.5}$ is also

consistent with many shear-resistance formulations, in which the concrete contribution is related to the square root of compressive strength rather than directly to f_{ck} .

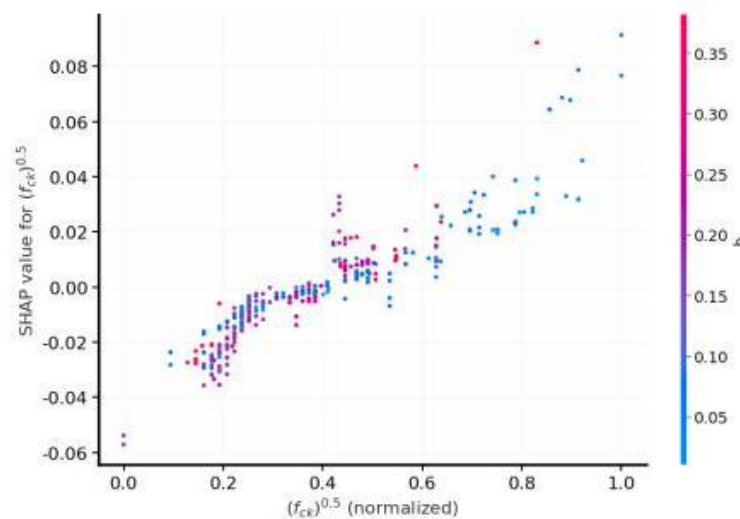


Fig. 22. SHAP plot for the influence of concrete strength on predicted shear capacity

7.4.5 Effect of Reinforcement-Related Variables

The reinforcement-related variables showed different levels of influence. The flexural reinforcement ratio, ρ_f , had a moderate positive effect on the predicted shear capacity. This is reasonable because the main reinforcement forms the tensile tie in the STM mechanism [8] and helps maintain equilibrium after cracking. The horizontal reinforcement ratio, ρ_h , also had a positive effect, but its global importance was smaller than that of the main geometric variables, a/d , and concrete strength.

The vertical reinforcement ratio, ρ_v , and the yield strength variables related to vertical or transverse reinforcement had relatively low SHAP importance. This result should not be interpreted to mean that these variables are unimportant in design. Rather, it indicates that within the present database their marginal contribution was smaller than that of geometry, concrete strength, and the shear span ratio. This may be due to the limited range of vertical reinforcement values, the distribution of test specimens in the database, or the fact that the primary resistance mechanism is governed by the diagonal compression strut and the main tension tie.

7.4.6 General Interpretation of The SHAP Findings

The SHAP analysis, in general, suggests that the XGBoost model learned trends that are broadly consistent with established corbel mechanics. The positive effects of h , b , w_c , and $(f_{ck})^{0.5}$ indicate the importance of member size, compression-zone development, and concrete strength. The negative effect of a/d confirms the dominant role of load-path geometry and the reduction in shear capacity as the corbel becomes less deep-beam-like. Reinforcement variables contributed positively but generally played a secondary role within the range of the compiled data.

Therefore, the value of the present ML component lies mainly in interpretation rather than prediction. The SHAP results provide an additional layer of explanation that connects data-driven modelling with the known mechanical behavior of RCCs. This supports the systematic review findings and helps translate the ML output into structural engineering language.

8. Discussion of ML Results

The SHAP analysis supports the main behavioral interpretation obtained from the systematic review. The results demonstrate that the XGBoost model did not only provide accurate predictions, but also captured trends that are consistent with the known mechanics of RCCs. The dominant influence of the geometric variables and the a/d ratio confirms that RCCs behavior is strongly

governed by the geometry of the compression strut, the size of the load-transfer region, and the directness of the load path between the bearing point and the column face. This finding agrees with the experimental evidence reviewed in Section 4, where smaller a/d ratios generally resulted in higher shear strength due to stronger direct strut action.

Before these rankings are read as statements of relative physical importance, the correlation structure among the dimensional inputs must be taken into account. The variables h , b , w_c , and d are not independent quantities in a corbel database. The effective depth d is by definition the total height h less the cover and the position of the main tension reinforcement, so the two are almost collinear by construction; the corbel width b and the column width w_c are tied to each other because the corbel is cast against the column and is normally proportioned to match or approach its width; and all four grow together because test specimens are usually scaled versions of a common geometry rather than independently varied dimensions. The shear span a_v and the ratio a/d are correlated with d for the same reason. This has a direct bearing on how Fig. 19 and Table 12 should be read. SHAP allocates the contribution of a prediction among the inputs actually used by the fitted trees, and when two inputs carry nearly the same information the ensemble will split on whichever one happens to reduce the loss first, so the attribution is divided between them in a manner that depends on the fitting sequence rather than on mechanics. The individual ranks of h , b , w_c , and d are therefore not stable quantities, and the difference between the mean absolute SHAP values of h (0.0296) and b (0.0284) is far too small to support a claim that height matters more than width. What the analysis does support is a statement at the level of the group: the four-dimensional variables together account for the largest share of the model output, which is the expected consequence of predicting a capacity, in units of force, rather than a normalized shear stress. Read this way, the correct interpretation of the SHAP ranking is that member size as a whole dominates, that a/d and $(f_{ck})^{0.5}$ contribute separately and with mechanically consistent signs, and that reinforcement variables act as secondary contributors. Two consequences follow for future work. Repeating the interpretation with $V_{exp}/(bd)$ as the target, as recommended in Section 9, removes much of the shared size information and would show whether the ranking of the geometric variables survives once the direct size effect is suppressed. In parallel, reporting variance inflation factors or a correlation matrix for the input set, as reported for the deep-beam input set in [146], and testing grouped or clustered SHAP attributions in which collinear variables are evaluated jointly, would make the division of importance among h , b , w_c , and d reproducible rather than fitting-dependent.

The positive contribution of concrete compressive strength is also consistent with the physical behavior of RCCs. Since the main load-transfer mechanism depends on the diagonal compression strut, an increase in concrete strength improves the resistance to diagonal compression, local crushing, and bearing-related distress. This explains why $(f_{ck})^{0.5}$ appeared among the most influential variables in the SHAP ranking. The use of this parameter is also reasonable from a mechanics-based perspective, since many shear-strength formulations relate the concrete contribution to square root of concrete compressive strength rather than to the direct value of f_{ck} .

The reinforcement-related variables showed positive but lower global SHAP importance compared with geometry, a/d , and concrete strength. This result should not be interpreted as evidence that reinforcement is unimportant in design. Rather, it indicates that within the range of the compiled database, the marginal contribution of reinforcement variables was smaller than the contribution of the main geometric and concrete-strength parameters. The flexural reinforcement ratio, ρ_f , had a moderate positive influence because the main reinforcement forms the tension tie in the strut-and-tie mechanism. The horizontal reinforcement ratio ρ_h , also contributed positively by improving crack control and confinement. In contrast, the vertical reinforcement ratio, ρ_v , and the yield-strength variables showed lower importance, which may be related to their narrower range in the database, their interaction with a/d , and the dominant role of the concrete strut in short corbels.

The SHAP findings also help explain why existing code-based models may show conservative or scattered predictions. Code equations are usually based on simplified assumptions, such as shear-friction action, an idealized strut-and-tie mechanism, or a triangular truss analogy. These models are useful for design because they are simple and mechanically meaningful, but they may not fully

represent the interaction among member size, a/d , concrete strength, reinforcement ratios, support width, and bearing condition. The SHAP results indicate that these variables do not act independently. Instead, the predicted capacity is controlled by a combined effect of geometry, material strength, and reinforcement arrangement. This supports the need to interpret code predictions together with experimental evidence and data-driven trends.

It is therefore worth stating precisely what the integration of machine-learning methods adds to the understanding of parameter influence, and where it does not replace mechanics-based reasoning. A mechanics-based model expresses a parameter's influence through the role assigned to it in an assumed load path: in the strut-and-tie idealization of Section 6.2, for instance, a/d enters through the strut inclination θ of Equation (9), and the concrete strength enters through the effective stresses $f_{ce,s}$ and $f_{ce,n}$ of Equations (15) and (16). The influence of a parameter is thus known in advance, by construction, and any parameter omitted from the idealization has no influence at all. The empirical alternative, a parametric test series, isolates one variable while holding the others fixed, which is rigorous but expensive and restricted to the few combinations that can be built and tested. Explainable ML occupies the space between these two. It infers the influence of every recorded variable simultaneously, across the full set of assembled specimens, without prescribing a load path in advance, and SHAP then decomposes each individual prediction into additive contributions so that both the magnitude and the sign of each variable's effect become visible. Four specific gains follow in the present case. First, the direction of the effects was recovered rather than imposed: the negative sign for a/d and the positive signs for the dimensional variables and for $(f_{ck})^{0.5}$ emerged from the data and coincide with the mechanics summarized in Table 7, which supplies independent corroboration of the review findings. Second, the method ranks parameters on a common quantitative scale, allowing the observation that reinforcement-related variables act as secondary contributors within this database, a comparison that the code equations cannot make because each of them carries a different subset of variables. Third, the dependence plots of Figs 20 to 22 expose the shape of each relationship and its interaction coloring, so that the coupling of a/d with a_v and d is visible directly rather than being assumed. Fourth, the analysis identifies where the evidence is thin: the low importance of ρ_v and f_{yv} is as much a statement about the coverage of the database as about the mechanics, which is diagnostic information that a closed-form equation cannot provide. The limits are equally definite. The model has no equilibrium condition and no failure criterion; its attributions are conditional on the fitted model and on the correlation, structure discussed above; and it cannot extrapolate beyond the parameter ranges of its 330 specimens. Explainable ML should therefore be understood as an instrument for interrogating the accumulated experimental evidence and for indicating which parameters a mechanics-based model must represent, not as a substitute for the mechanical reasoning that design provisions require.

The value of SHAP analysis in this study lies mainly in improving the interpretability of the ML model. Unlike accuracy indices such as R^2 and RMSE, SHAP values explain how each input variable contributes to the model prediction. This allows the ML output to be discussed in structural engineering terms rather than being treated as a black-box result. In the present study, the agreement between SHAP trends and established corbel mechanics gives confidence that the model learned meaningful behavioral patterns from the database. However, the interpretation remains dependent on the selected model, the distribution of the input variables, and the normalization of the output variable.

It should also be noted that the high importance of dimensional variables such as h , b , and w_c is partly related to the use of experimental shear capacity as the prediction target. Since the output represents normalized capacity rather than a normalized shear-stress index, member size naturally becomes influential. Therefore, future work should repeat the SHAP interpretation using normalized shear stress, such as $V_{exp}/(bd)$, to examine whether the variable ranking remains stable when the direct size effect is reduced. This would provide an additional view of the relative importance of geometry, concrete strength, and reinforcement.

In general, the SHAP analysis confirms that explainable ML can provide useful support to systematic review and mechanics-based interpretation. It should not be used as a substitute for design provisions, but it can help identify the most influential parameters, reveal database trends,

and clarify how different variables interact in predicting RCCs shear capacity. This combined approach provides a useful bridge between experimental evidence, code-based design models, and data-driven interpretation.

9. Limitations of the ML Interpretability Analysis

Although this study provides a systematic review and SHAP-based interpretation of RCCs shear capacity, several limitations should be acknowledged:

- Although the search was based mainly on Scopus and Web of Science and was supported by reference checking, some reports, theses, conference papers, or non-English studies may have been missed. Therefore, the collected studies should be viewed as a structured review database rather than a complete record of all corbel research.
- The reviewed works also varied in geometry, concrete type, reinforcement, loading setup, and testing method, which limits direct comparison. Non-conventional corbels, such as strengthened, repaired, fibre-reinforced, recycled aggregate, UHPC, and SCC specimens, were discussed qualitatively but were not included in the ML dataset to maintain consistency.
- The analytical and code-based review was used to clarify the assumptions and limits of selected design models, not to recalibrate design provisions. Similarly, the XGBoost model was trained on 330 mainly vertical-load specimens, so its predictions should be used carefully outside this range, and the combined H/V loading case is treated separately [145].
- The difference between the training and testing coefficients of determination, 0.9973 and 0.9090, indicates mild overfitting. A low learning rate, row and column subsampling were applied as regularization measures, but the residual gap reflects the limited size of the training sample relative to the 13-dimensional input space. The testing value should therefore be taken as the indicator of predictive performance, and the model should be used only as an explanatory instrument.
- The SHAP results depend on the dataset and model structure. Since some variables are physically correlated, as discussed in Section 8, their importance should be interpreted at the level of variable groups rather than individual ranks. Future work should expand the database, include uncertainty analysis, use normalized shear stress such as $V_{\text{exp}}/(bd)$, and develop separate models for strengthened, repaired, cyclic, and special-material corbels.
- The qualitative synthesis was limited by inconsistent reporting across primary studies. Key gaps included bearing and reinforcement detailing, geometric and material properties, cracking, and load-deflection data, failure modes, fibre characteristics, specimen age and curing, and repeated-loading protocols. Consistent reporting of these variables through a minimum dataset would enable broader quantitative synthesis, including serviceability behavior, and support future interpretable models.

10. Conclusions and Recommendations

This study presented a systematic review and SHAP-based interpretation of ML predictions for the shear capacity of reinforced concrete corbels. A structured PRISMA-guided review was conducted using Scopus and Web of Science records, supplemented by reference checking. After duplicate removal and screening, 121 studies were retained for qualitative synthesis. In addition, an XGBoost model was trained using 330 compatible vertical-load corbel specimens and interpreted using SHAP analysis. Based on the reviewed literature, analytical models, code provisions, and explainable ML results, the following conclusions can be drawn:

- The reviewed literature confirms that RCCs behave as discontinuity regions in which the applied load is transferred mainly through a diagonal compression strut, main tension reinforcement, secondary reinforcement, and nodal zones. Therefore, their shear behavior cannot be fully represented using ordinary sectional design assumptions.
- The a/d ratio is one of the most influential parameters affecting RCCs behavior. Lower a/d ratios promote direct strut action and generally increase shear capacity, while larger a/d ratios reduce the efficiency of the compression strut and increase the contribution of flexural and diagonal cracking mechanisms.

- Concrete compressive strength has a clear positive influence on cracking load, stiffness, and ultimate shear capacity. This effect is mainly related to the capacity of the diagonal compression strut and nodal regions. However, higher concrete strength may also increase brittleness, especially when adequate transverse reinforcement or fibre reinforcement is not provided.
- Longitudinal reinforcement plays an important role as the main tension tie in the strut-and-tie mechanism. Increasing the flexural reinforcement ratio generally improves ultimate capacity and post-cracking response, but excessive reinforcement may shift the failure mechanism toward concrete crushing, nodal distress, or less ductile behavior.
- Horizontal and vertical stirrups improve crack control, confinement, and deformation capacity. Horizontal reinforcement is generally effective in intercepting diagonal cracks and reducing brittle splitting, while vertical reinforcement contributes mainly to diagonal crack control and becomes more effective depending on the a/d ratio and the inclination of the compression strut.
- Column load appears to have limited influence on the ultimate shear capacity of RCCs, but it may improve serviceability by delaying crack initiation and reducing crack width near the corbel-column junction. Therefore, its effect should be interpreted mainly in relation to cracking behavior rather than as a direct strength-enhancement parameter.
- Repeated and cyclic loading can lead to stiffness degradation, wider cracks, accumulated damage, and reduced load-carrying capacity. These findings indicate that corbels subjected to crane loads, seismic actions, or repeated service loading require careful attention to ductility, crack control, and long-term performance.
- Strengthening and repair studies show that CFRP sheets, NSM reinforcement, steel plates, basalt-fibre systems, and fibre-reinforced repair materials can improve the capacity and serviceability of deficient or damaged RCCs. However, strengthened corbels may fail through debonding, peeling, anchorage distress, or brittle rupture. Therefore, these specimens should be treated separately from original unstrengthened corbels when developing shear-capacity databases or ML models.
- Strengthening effectiveness depended more on anchorage, development length, layup, and substrate condition than material quantity, highlighting the need for failure-mechanism-based rehabilitation design.
- The reviewed analytical and code-based models, including SFM, STM, and TTM approaches, provide useful design procedures. However, their predictions may be conservative or scattered because they are based on simplified assumptions and do not always capture the interaction among geometry, concrete strength, reinforcement ratios, support dimensions, and bearing conditions.
- The XGBoost model achieved good predictive performance for the compatible vertical-load dataset, with R^2 values of 0.9973 and 0.9090 for the training and testing sets, respectively. These results indicate that the model can capture the nonlinear relationship between the input variables and normalized experimental shear capacity. The gap between the two values reflects mild overfitting that the applied regularization measures reduced but did not eliminate, so the testing value should be regarded as the indicator of predictive performance. The model was used in this study for interpretation rather than as a new design equation.
- SHAP analysis demonstrated that corbel height, corbel width, column width, a/d , and concrete compressive strength were the most influential variables in the XGBoost model. This ranking is consistent with the mechanics of RCCs, where member geometry, strut configuration, and concrete strength govern the main load-transfer mechanism. Because the dimensional variables are mutually correlated, the ranking should be read at the level of the group rather than as a strict ordering of individual variables.
- Reinforcement-related variables showed positive but comparatively lower SHAP importance within the collected database. This does not mean that reinforcement is unimportant in design. Rather, it indicates that the marginal influence of reinforcement variables in the present dataset was smaller than that of geometry, a/d , and concrete strength, and it also reflects the limited range over which some reinforcement parameters were varied in the available tests.

As a recommendation, further research is suggested to expand the experimental database and develop separate interpretable models for strengthened, repaired, special-material, and cyclically loaded corbels. Future studies should also conduct SHAP analysis using normalized shear stress, such as $V_{exp}/(bd)$, to examine whether the relative importance of variables remains stable after reducing the direct size effect. In addition, a minimum reporting data set for corbel experiments, covering bearing dimensions, anchorage detailing, the k/h ratio, cracking loads and crack widths, the complete load-deflection response, and failure modes, would allow future studies to address serviceability as well as ultimate behavior.

Acknowledgement

The authors gratefully acknowledge the Iraqi Ministry of Higher Education and Scientific Research for providing access to Scopus and Web of Science through national or institutional subscriptions. This access supported the literature search, screening, and retrieval of the studies used in this systematic review.

References

- [1] Lacerda MMS, da Silva TJ, Alva GMS, de Lima MCV. Influence of the vertical grouting in the interface between corbel and beam in beam-to-column connections of precast concrete structures - An experimental analysis. *Eng Struct*. 2018; 172:201-213. <https://doi.org/10.1016/j.engstruct.2018.06.012>
- [2] Abbas MK, Ali AY. Structural response of reinforced concrete corbels under repeated and combined loading: scoping review. *IOP Conf Ser Earth Environ Sci*. 2025;1545(1):012068. <https://doi.org/10.1088/1755-1315/1545/1/012068>
- [3] Hassan MA, Darwish MN, Allam SM, Diab MA. Experimental study on two-step concrete corbels with several interface conditions. *Adv Civ Eng*. 2023; 2023:8812336. <https://doi.org/10.1155/2023/8812336>
- [4] de Lima Araujo D, Azevedo Coelho S, Regina Mesquita de Almeida S, El Debs MK. Computational modelling and analytical model for two-step corbel for precast concrete system. *Eng Struct*. 2021; 244:112699. <https://doi.org/10.1016/j.engstruct.2021.112699>
- [5] Lee TM, Lu WY, Lin GZ. Shear strength prediction for reinforced concrete corbels. *ACI Struct J*. 2000;97(4):13-26. <https://doi.org/10.14359/8796>
- [6] Ahmed MM, Diab H, Drar AAM. Shear behavior of high strength fiber reinforced concrete corbels. *J Eng Sci*. 2012;40(4):969-987. <https://doi.org/10.21608/jesaun.2012.114704>
- [7] Abu-Obaida A, El-Maaddawy T, El-Ariss B. Numerical simulation of double-sided concrete corbels internally-reinforced with GFRP bars. *Compos Part C Open Access*. 2020;2:100040. <https://doi.org/10.1016/j.jcomc.2020.100040>
- [8] Allen MN, El-Salakawy EF. Experimental behavior of concrete corbels reinforced with glass fiber-reinforced polymer headed-end bars. *ACI Struct J*. 2024;121(3):231-243. <https://doi.org/10.14359/51740616>
- [9] ACI Committee 318. Building Code Requirements for Structural Concrete (ACI CODE-318-25) and Commentary. Farmington Hills, MI: American Concrete Institute; 2025.
- [10] British Standards Institution. BS EN 1992-1-1: Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings. London: BSI; 2004.
- [11] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Code for Design of Concrete Structures: GB 50010-2010. Beijing: China Architecture & Building Press; 2010.
- [12] Wilson HR, Yousefpour H, Brown MD, Bayrak O. Investigation of corbels designed according to strut-and-tie and empirical methods. *ACI Struct J*. 2018;115(3):813-824. <https://doi.org/10.14359/51701923>
- [13] Abbas MK, Ali AY. Experimental data-driven neural network model for predicting RC corbel shear strength via a web-based interface. *Multiscale Multidiscipl Model Exp Des*. 2025;8(8):352. <https://doi.org/10.1007/s41939-024-00621-3>
- [14] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71. <https://doi.org/10.1136/bmj.n71>
- [15] Kriz LB, Rath CH. Connections in precast concrete structures - strength of corbels. *PCI J*. 1965;10(1):16-61. <https://doi.org/10.15554/pcij.02011965.16.61>
- [16] Yong Y, Balaguru P. Behavior of reinforced high-strength-concrete corbels. *J Struct Eng*. 1994;120(4):1182-1201. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1994\)120:4\(1182](https://doi.org/10.1061/(ASCE)0733-9445(1994)120:4(1182)
- [17] Mattock AH, Chen KC, Soongswang K. The behavior of reinforced concrete corbels. *PCI J*. 1976;21(2):52-77. <https://doi.org/10.15554/pcij.03011976.52.77>
- [18] Aliewi JM. A modified formula to predict the ultimate load capacity of reinforced concrete corbels. *J Eng Sustain Dev*. 2019;23(2):165-183. <https://doi.org/10.31272/jeasd.23.2.13>

- [19] Al-Quraishi H, Fuad A. Finite element analysis of UHPC corbels. *J Eng.* 2017;23(9):78-88. <https://doi.org/10.31026/j.eng.2017.09.06>
- [20] Joshi DD, Patel PV. Experimental assessment of dry precast beam column connections under progressive collapse scenario. *J Struct Eng.* 2016;142(10):04016086. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001550](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001550)
- [21] Gulsan ME, Cevik A, Mohmmad SH. Crack pattern and failure mode prediction of SFRC corbels: experimental and numerical study. *Comput Concr.* 2021;28(5):507-522. <https://doi.org/10.12989/cac.2021.28.5.507>
- [22] Medina AL, Estores GB. Assessment of two-sided concrete corbel with different structural forms using finite element modeling. *Civ Eng Archit.* 2024;12(2):822-839. <https://doi.org/10.13189/cea.2024.120213>
- [23] Maksymovych S, Karkhut I. Research on the strength and crack resistance of reinforced concrete short corbels. In: Blikharskyy Z, Katunsky D, Licholai L, editors. *Proceedings of CEE 2024*. Cham: Springer; 2025. p. 213-227. https://doi.org/10.1007/978-3-031-72211-0_18
- [24] Lu WY, Lin IJ. Behavior of reinforced concrete corbels. *Struct Eng Mech.* 2009;33(3):357-371. <https://doi.org/10.12989/sem.2009.33.3.357>
- [25] Mohammed HS, Ali AY. Structural behavior of reinforced concrete corbels with vertical openings. *Math Model Eng Probl.* 2025;12(4):1457-1466. <https://doi.org/10.18280/mmep.120422>
- [26] Sayhood EK, Mohammed NS, Resheq AS. Shear strength capacity of reinforced concrete corbels. *Tikrit J Eng Sci.* 2024;31(4):70-75. <https://doi.org/10.25130/tjes.31.4.7>
- [27] ACI Committee 318. *Building Code Requirements for Structural Concrete (ACI 318M-19) and Commentary*. Farmington Hills, MI: American Concrete Institute; 2019.
- [28] Wight JK, MacGregor JG. *Reinforced Concrete: Mechanics and Design*. 5th ed. Upper Saddle River, NJ: Pearson Prentice Hall; 2009.
- [29] Borgohain A. Behavior of concrete corbels reinforced with GFRP bent bars [master's thesis]. Winnipeg (MB): University of Manitoba; 2023.
- [30] Mohamed O, Hamdy G, Ismail AM. Experimental study of reinforced concrete double corbels containing steel fibers subjected to eccentric vertical loads. *Eng Res J.* 2025;48(1):45-56. <https://doi.org/10.21608/erjm.2025.341201>
- [31] Amaral RR, Gomes HM, Tamayo JLP. Optimized strut-and-tie design for double-sided corbels using multi-material topology optimization under multiple load cases. *Int J Mech Mater Des.* 2025;21(3):641-665. <https://doi.org/10.1007/s10999-024-09728-w>
- [32] Abdul-Razzaq KS, Dawood AA, Jalil AM. Analysis of unsymmetrical reinforced concrete double corbels. *AIP Conf Proc.* 2020;2213(1):020162. <https://doi.org/10.1063/5.0000168>
- [33] Kheyroddin A, Raygan S, Kioumars M. Optimizing corbel reinforcement through nonlinear analysis: determining superiority of steel bars or CFRP. *Lect Notes Civ Eng.* 2025; 237:1501-1513. https://doi.org/10.1007/978-3-031-32519-9_115
- [34] Huang H, Xue C, Wang Z. Experimental and numerical simulation study on shear performance of RC corbel under synergistic change in inclination angle. *Buildings.* 2025;15(17):3098. <https://doi.org/10.3390/buildings15173098>
- [35] Naser KZ, Almayah AA, Abbas AM. Shear strength and behavior of eco-friendly RC corbels. *Results Eng.* 2025;25:104101. <https://doi.org/10.1016/j.rineng.2024.104101>
- [36] Sulaiman EA, Khudair J. Effect of using recycled concrete aggregate on behavior of RC corbels cast with self-compacting concrete (experimental and analytical study). *Kufa J Eng.* 2020;11(1):1-21. <https://doi.org/10.30572/2018/kje/110101>
- [37] Hamoodi AZ, Chkheiwier AH, Kadim JA. Shear strength of reinforced recycled aggregate concrete corbels. *J Eng.* 2021; 2021:6652647. <https://doi.org/10.1155/2021/6652647>
- [38] Al-Badiri RAR, Al-Thairy HAB. Experimental and numerical study of eco-friendly corbels under static loading. *Eurasia Proc Sci Technol Eng Math.* 2025; 37:553-573. <https://doi.org/10.55267/iadt.2025.37.553>
- [39] Kheyroddin A, Raygan S, Kioumars M. Strut and tie model for CFRP strengthened reinforced concrete corbels. *Eng Struct.* 2024;304:117609. <https://doi.org/10.1016/j.engstruct.2024.117609>
- [40] Kurtoglu AE, Gulsan ME, Abdi HA, Kamil MA, Cevik A. Fiber reinforced concrete corbels: modeling shear strength via symbolic regression. *Comput Concr.* 2017;20(1):65-75. <https://doi.org/10.12989/cac.2017.20.1.065>
- [41] Alazzawi A. Experimental investigation on the behavior of reinforced concrete corbels under repeated loadings. *J Eng Dev.* 2015;19(4):126-147.
- [42] Beshara FBA, Mustafa TS, Mahmoud AA, Khalil MMA. Constitutive models for nonlinear analysis of SFRC corbels. *J Build Eng.* 2020; 28:101092. <https://doi.org/10.1016/j.jobbe.2019.101092>
- [43] Abdul-Razzaq KS, Dawood AA. Corbel strut and tie modeling - experimental verification. *Structures.* 2020; 26:327-339. <https://doi.org/10.1016/j.istruc.2020.04.032>

- [44] Lei H, Wu F, Gao L, Yan J, Huang H. Experimental study and kinematics-based approach for shear strength assessment of RC corbels with variously inclined reinforcement. Eng Struct. 2025; 341:120830. <https://doi.org/10.1016/j.engstruct.2025.120830>
- [45] Fattuhi NI. Column-load effect on reinforced concrete corbels. J Struct Eng. 1990;116(1):188-197. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1990\)116:1\(188](https://doi.org/10.1061/(ASCE)0733-9445(1990)116:1(188)
- [46] Neuberger YM, de Andrade Silva F, de Lima MCV, Reginato L, El Debs MK. Numerical analysis of reinforced concrete corbels using concrete damage plasticity: sensitivity to material parameters and comparison with analytical models. Buildings. 2023;13(11):2781. <https://doi.org/10.3390/buildings13112781>
- [47] Hermansen BR, Cowan J. Modified shear-friction theory for bracket design. ACI J Proc. 1974;71(2):55-60. <https://doi.org/10.14359/11181>
- [48] Yassin LAG, Sayhood EK, Hasan QA. Reinforced concrete corbels - state of the art. J Mater Eng Struct. 2015;2(1):180-205.
- [49] Li SS, Zheng JY, Li HM, Guo Y, Zhang Y, Wang Y. Analysis of shear model for steel-fiber-reinforced high-strength concrete corbels with welded-anchorage longitudinal reinforcement. Materials. 2023;16(14):4907. <https://doi.org/10.3390/ma16144907>
- [50] Canha RMF, Kuchma DA, El Debs MK, de Souza RA. Numerical analysis of reinforced high strength concrete corbels. Eng Struct. 2014;74:130-144. <https://doi.org/10.1016/j.engstruct.2014.05.014>
- [51] Md Zin N, Al-Fakih A, Nikbakht E, Teo W, Gad MA. Influence of secondary reinforcement on behavior of corbels with various types of high-performance fiber-reinforced cementitious composites. Materials. 2019;12(24):4159. <https://doi.org/10.3390/ma12244159>
- [52] Nguyen PD, Dang VH. Shear strength of hybrid GFRP-steel reinforced concrete corbels without vertical stirrups: experimental research and prediction models. Structures. 2024; 68:107031. <https://doi.org/10.1016/j.istruc.2024.107031>
- [53] Shakir QM, Abdlsaheb SD. Rehabilitation of partially damaged high strength RC corbels by EB FRP composites and NSM steel bars. Structures. 2022; 38:652-671. <https://doi.org/10.1016/j.istruc.2022.02.030>
- [54] Fattuhi NI, Hughes BP. Ductility of reinforced concrete corbels containing either steel fibers or stirrups. ACI Struct J. 1989;86(6):644-651. <https://doi.org/10.14359/2816>
- [55] Nagrodzka-Godycka K. Reinforced concrete corbels with spiral reinforcement. Arch Civ Eng. 2001;47(4):461-477.
- [56] Prasad HNR, Channakeshava C, Prasad BKR, Iyengar KTSR. Nonlinear finite element analysis of reinforced concrete corbel. Comput Struct. 1993;46(2):343-354. [https://doi.org/10.1016/0045-7949\(93\)90200-8](https://doi.org/10.1016/0045-7949(93)90200-8)
- [57] Rezaei M, Osman SA, Shanmugam NE. Primary and secondary reinforcements in reinforced concrete corbels. J Civ Eng Manag. 2013;19(6):836-845. <https://doi.org/10.3846/13923730.2013.801899>
- [58] Abdul-Razzaq KS, Dawood AA, Mohammed AH. A review of previous studies on the reinforced concrete corbels. IOP Conf Ser Mater Sci Eng. 2019;518(2):022057. <https://doi.org/10.1088/1757-899X/518/2/022057>
- [59] Shakir QM. Analysis, behavior, strengthening and repairing of reinforced concrete corbels: comprehensive review. J Mater Eng Struct. 2023;10(1):157-184.
- [60] Yassin LAG, Sayhood EK, Hasan QAM. Reinforced concrete corbels - state of the art. J Mater Eng Struct. 2015;2(1):180-205.
- [61] Chetchotisak P, Teerawong J, Yindeesuk S. Modified interactive strut-and-tie modeling of reinforced concrete deep beams and corbels. Structures. 2022; 45:284-298. <https://doi.org/10.1016/j.istruc.2022.09.022>
- [62] Hwang SJ, Lee HJ. Strength prediction for discontinuity regions by softened strut-and-tie model. J Struct Eng. 2002;128(12):1519-1526. [https://doi.org/10.1061/\(ASCE\)0733-9445\(2002\)128:12\(1519](https://doi.org/10.1061/(ASCE)0733-9445(2002)128:12(1519)
- [63] Cattaneo S, Crespi P, Biolzi L. Structural analysis and design of reinforced concrete bridge corbels. Appl Sci. 2020;10(19):6727. <https://doi.org/10.3390/app10196727>
- [64] Shakir QM, Abdlsaheb SD. Strengthening of the self-compacted reinforced concrete corbels using NSM steel bars and CFRP sheets techniques. J Eng Sci Technol. 2022;17(3):1764-1780.
- [65] Faleh SK, Chkheiwier AH, Saleh IS. Structural behavior of high-strength concrete corbels involving steel fibers or closed stirrups. Period Eng Nat Sci. 2022;10(1):239-252. <https://doi.org/10.21533/pen.v10i1.2612>
- [66] Clottey BCN. Performance of lightweight concrete corbels subjected to static and repeated loads [master's thesis]. Stillwater (OK): Oklahoma State University; 1977.
- [67] Huang Y, Peng L, Wei H. Finite element analysis of the shear performance of reinforced concrete corbels under different design codes. Buildings. 2024;14(10):3100. <https://doi.org/10.3390/buildings14103100>

- [68] Borgohain A, Bediwy AG, El-Salakawy EF. Practical evaluation of high-strength concrete corbels reinforced with GFRP bent bars. Eng Struct. 2024; 299:117095. <https://doi.org/10.1016/j.engstruct.2023.117095>
- [69] Abdulqader S, Al-Shathir B, Hasan A. Experimental behavior of self-compacting concrete corbels strengthened with external CFRP. Eng Technol J. 2018;36(2A):154-162. <https://doi.org/10.30684/etj.36.2A.6>
- [70] Mattock AH. Design proposals for reinforced concrete corbels. PCI J. 1976;21(3):18-42. <https://doi.org/10.15554/pcij.05011976.18.42>
- [71] Li HM, Zheng JY, Li SS. Shear bearing capacity prediction of steel-fiber-reinforced high-strength concrete corbels on modified compression field theory. Buildings. 2024;14(2):388. <https://doi.org/10.3390/buildings14020388>
- [72] Li SS, Zheng JY, Li HM, Guo Y, Zhang Y. Prediction of shear strength for steel-fiber high-strength concrete corbels with the softened strut-and-tie model. Buildings. 2023;13(4):1107. <https://doi.org/10.3390/buildings13041107>
- [73] Li SS, Zheng JY, Li HM, Guo Y, Zhang Y. Experimental investigation on shear capacity of steel-fiber-reinforced high-strength concrete corbels. Materials. 2023;16(8):3055. <https://doi.org/10.3390/ma16083055>
- [74] Qasim OA, Farhan OS. Corbels structural behavior of reinforced lightweight recycled concrete. AIP Conf Proc. 2025;3225(1):110015. <https://doi.org/10.1063/5.0250917>
- [75] Kumar BS, Seshu DR. An experimental study on the interface shear strength of reinforced geopolymer concrete corbels. Aust J Civ Eng. 2022;20(2):359-373. <https://doi.org/10.1080/14488353.2021.1983577>
- [76] Zaioune H, Mezhoud S. Numerical analysis of behavior of corbels strengthened with carbon fiber-reinforced polymer. Iran J Sci Technol Trans Civ Eng. 2023;47(4):2149-2171. <https://doi.org/10.1007/s40996-023-01046-2>
- [77] Othman ZS, Aziz OQ. Ultimate shear strength of reinforced high strength concrete corbels subjected to vertical load. Al-Rafidain Eng J. 2010;18(1):1-12. <https://doi.org/10.33899/mjaes.2010.5593>
- [78] Wongtala P, Chaimoon N, Khomwan N, Chaimoon K. Experimental and numerical study on structural behavior of reactive powder concrete corbels without stirrups. Case Stud Constr Mater. 2023;19:e02372. <https://doi.org/10.1016/j.cscm.2023.e02372>
- [79] Al-Allaf MH, Daud RA, Daud SA. Nonlinear finite element analysis of concrete corbels with hybrid reinforcements. Mech Adv Mater Struct. 2025;32(21):5245-5255. <https://doi.org/10.1080/15376494.2024.2393356>
- [80] Abdul-Razzak AA, Mohammed Ali AA. Modelling and numerical simulation of high strength fibre reinforced concrete corbels. Appl Math Model. 2011;35(6):2901-2915. <https://doi.org/10.1016/j.apm.2010.11.071>
- [81] Chkheiwier AH, Ahmed MA, Naser KZ. Modified prediction approach of strength of high strength polyolefin fiber reinforced concrete corbels. Period Eng Nat Sci. 2021;9(2):1141-1151. <https://doi.org/10.21533/pen.v9i2.2037>
- [82] Hassan A, Ellithy M, El-Shafiey TF. Upgrading the shear strength of reinforced concrete corbels using strain hardening cementitious composites. Eng Struct. 2022;273:115047. <https://doi.org/10.1016/j.engstruct.2022.115047>
- [83] Attiya MA, Kamonna HH. Performance of steel fiber-reinforced concrete corbels without secondary reinforcement. AIP Conf Proc. 2023;2806(1):020003. <https://doi.org/10.1063/5.0163351>
- [84] Fattuhi NI. Strength of SFRC corbels subjected to vertical load. J Struct Eng. 1990;116(3):701-718. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1990\)116:3\(701](https://doi.org/10.1061/(ASCE)0733-9445(1990)116:3(701)
- [85] Saleh IS, Faleh SK, Mahdi MS. Effects of fiber type and shape on the shear behavior of reinforced concrete corbels without hoop re-bars. Civ Eng J. 2022;8(3):519-530. <https://doi.org/10.28991/CEJ-2022-08-03-09>
- [86] Khalifa ES. Macro-mechanical strut and tie model for analysis of fibrous high-strength concrete corbels. Ain Shams Eng J. 2012;3(4):359-365. <https://doi.org/10.1016/j.asej.2012.04.009>
- [87] Mahdi MT, Naghipour M, Hemzah SA. Structural behavior of steel-concrete hybrid corbels with steel reinforcement. Structures. 2026;88:111813. <https://doi.org/10.1016/j.istruc.2025.111813>
- [88] Shabbir F, Khan MI, Ahmad N, Alizai MJ, Hameed A, Usman M. Experimental and numerical investigation of construction defects in reinforced concrete corbels. Buildings. 2023;13(9):2247. <https://doi.org/10.3390/buildings13092247>
- [89] Borgohain A, Bediwy AG, El-Salakawy EF. Performance of GFRP-reinforced concrete corbels under monotonic loading. J Compos Constr. 2024;28(1):04023056. [https://doi.org/10.1061/\(CCOF2.CCENG-4340](https://doi.org/10.1061/(CCOF2.CCENG-4340)

- [90] Kamal MD, Yaseen SA. Experimental investigation on shear behavior of double sided reinforced concrete corbels using BFRP bars. ZANCO J Pure Appl Sci. 2026;38(1):162-176. <https://doi.org/10.21271/ZJPAS.38.1.15>
- [91] Kumar S, Barai SV. Neural networks modeling of shear strength of SFRC corbels without stirrups. Appl Soft Comput. 2010;10(1):135-148. <https://doi.org/10.1016/j.asoc.2009.06.012>
- [92] Yang JM, Lee JH, Yoon YS, Cook WD, Mitchell D. Influence of steel fibers and headed bars on the serviceability of high-strength concrete corbels. J Struct Eng. 2012;138(1):123-129. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000427](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000427)
- [93] Ridha MMS, Al-Shafi'i NTH, Hasan MM. Ultra-high performance steel fibers concrete corbels: experimental investigation. Case Stud Constr Mater. 2017; 7:180-190. <https://doi.org/10.1016/j.cscm.2017.07.003>
- [94] Dawood AA, Kadhum AK, Abdul-Razzaq KS. Strength of reinforced concrete corbels - a parametric study. Int J Civ Eng Technol. 2018;9(11):2274-2288.
- [95] Kassem W. Strength prediction of corbels using strut-and-tie model analysis. Int J Concr Struct Mater. 2015;9(2):255-266. <https://doi.org/10.1007/s40069-015-0102-y>
- [96] Ozden S, Atalay HM. Strengthening of reinforced concrete corbels with GFRP overlays. Sci Eng Compos Mater. 2011;18(1-2):69-77. <https://doi.org/10.1515/secm.2011.011>
- [97] Shakir QM. Response of innovative high strength reinforced concrete encased-composite corbels. Structures. 2020; 25:798-809. <https://doi.org/10.1016/j.istruc.2020.03.048>
- [98] Somerville G. The behavior and design of reinforced concrete corbels. ACI Spec Publ. 1974;42:477-502. <https://doi.org/10.14359/17282>
- [99] Halim NHFA, Adnan A, Kadir MAA, Ramli Z. Comparison of modified precast concrete corbel and nib connections under cyclic loading: numerical assessment. Innov Infrastructure Solut. 2026;11(3):112. <https://doi.org/10.1007/s41062-025-01890-4>
- [100] Liu H, Kong P, Ye T. Influence of precast member corbels on seismic performance of precast beam-slab-column joints. Adv Civ Eng. 2021; 2021:7107569. <https://doi.org/10.1155/2021/7107569>
- [101] Yassin LAG. Behavior of RC corbels strengthened with CFRP under monotonic and repeated loading [doctoral dissertation]. Baghdad: University of Technology; 2016.
- [102] Sayhood EK, Hassan QAM, Yassin LAG. Enhancement in the load-carrying capacity of reinforced concrete corbels strengthened with CFRP strips under monotonic or repeated loads. Eng Technol J. 2016;34(14):2705-2719. <https://doi.org/10.30684/etj.34.14A.11>
- [103] Ibrahim ES, Abdulrahman MB, Yahia YI, Alsubari B, Abdulaali HS, Alqawzai S. Behavior of reinforced concrete corbels strengthened with CFRP strips subjected to monotonic and repeated loading. Tikrit J Eng Sci. 2024;31(1):88-100. <https://doi.org/10.25130/tjes.31.1.9>
- [104] Al-Taie FJ, Ahmed AM. Structural behavior of reinforced concrete corbel using high-strength materials under monotonic and repeated loads. Int J Appl Sci. 2019;2(2):p1. <https://doi.org/10.30560/ijas.v2n2p1>
- [105] Ivanova I, Assih J. The effect of fatigue test on short reinforced-concrete corbel strengthened by externally bonded composite fibre fabrics. Eng Fract Mech. 2016; 167:167-175. <https://doi.org/10.1016/j.engfracmech.2016.04.018>
- [106] Ivanova I, Assih J. Static and dynamic experimental study of strengthened reinforced short concrete corbel by using carbon fabrics, crack path in shear zone. Frattura ed Integrità Strutturale. 2015;9(34):90-98. <https://doi.org/10.3221/IGF-ESIS.34.09>
- [107] Reginato L, de Sousa AMD, Santos JVC, El Debs MK. NLFEA of reinforced concrete corbels: proposed framework, sensibility study, and precision level. Buildings. 2023;13(7):1874. <https://doi.org/10.3390/buildings13071874>
- [108] Stankov V, Ivanova I, Assih J, Dontchev D. Numerical modeling of mechanical behavior of a reinforced concrete column-short corbel assembly strengthened by bonding a CFRF. IOP Conf Ser Mater Sci Eng. 2023;1276(1):012023. <https://doi.org/10.1088/1757-899X/1276/1/012023>
- [109] Al-Kamaki YSS, Hassan GB, Alsofi G. Experimental study of the behavior of RC corbels strengthened with CFRP sheets. Case Stud Constr Mater. 2018;9:e00181. <https://doi.org/10.1016/j.cscm.2018.e00181>
- [110] Abdulrahman MB, Salih SA, Abduljabbar RJ. The assessment of using CFRP to enhance the behavior of high strength reinforced concrete corbels. Tikrit J Eng Sci. 2021;28(1):71-83. <https://doi.org/10.25130/tjes.28.1.6>
- [111] Assih J, Ivanova I, Dontchev D, Li A. Concrete damaged analysis in strengthened corbel by external bonded carbon fibre fabrics. Appl Adhes Sci. 2015;3(1):12. <https://doi.org/10.1186/s40563-015-0043-4>
- [112] Ivanova I, Assih J, Li A, Dontchev D, Delmas Y. Experimental investigation into strengthened short reinforced concrete corbels by bonding carbon fiber fabrics. J Adhes Sci Technol. 2015;29(20):2176-2189. <https://doi.org/10.1080/01694243.2015.1060049>
- [113] Shakir QM, Alsaheb SDA. High strength self-compacting corbels retrofitted by near surface mounted steel bars. Pollack Period. 2023;18(1):106-112. <https://doi.org/10.1556/606.2022.00661>

- [114] Hassan HSM, Ali AY. A new strengthening technique for reinforced concrete corbels openings using steel plates. IOP Conf Ser Earth Environ Sci. 2024;1374(1):012082. <https://doi.org/10.1088/1755-1315/1374/1/012082>
- [115] Fadel MA, Waryosh WA. Behavior of normal and high strength reinforced concrete corbels strengthened with steel plates. Eng Technol Appl Sci Res. 2025;15(5):26194-26203. <https://doi.org/10.48084/etasr.11210>
- [116] Hashim DT, Abdulghani AW, Albegmpri HMA. Case study of shear strengthening of RC corbels by steel plates using FEA. East Eur J Enterp Technol. 2023;2(7-122):50-60. <https://doi.org/10.15587/1729-4061.2023.275463>
- [117] Gulsan ME, Al Jawahery MS, Alshawaf AH, Hussein TA, Abdulhaleem KN, Cevik A. Rehabilitation of normal and self-compacted steel fiber reinforced concrete corbels via basalt fiber. Adv Concr Constr. 2018;6(5):423-463. <https://doi.org/10.12989/acc.2018.6.5.423>
- [118] Bobek L, Klusacek L, Svoboda A. Effective strengthening of reinforced concrete corbels using post-tensioning. Eng Struct. 2024; 305:117716. <https://doi.org/10.1016/j.engstruct.2024.117716>
- [119] Ivanova I. Repairing of short reinforced concrete corbel by bonding composite material under continuous load. In: Proceedings of the 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures (FraMCoS-10); 2019 Jun 23-26; Bayonne, France. 2019. <https://doi.org/10.21012/FC10.247414>
- [120] Aborgheef S, Abdulridha AJ. Optimizing different damaged reinforced concrete corbel characteristics utilizing CFRP sheets. Frattura ed Integrità Strutturale. 2025;19(74):31-41. <https://doi.org/10.3221/IGF-ESIS.74.03>
- [121] Ivanova I, Assih J, Dontchev D. Influence of anchorage length of composite fabrics and bonded surface on the strengthened short reinforced concrete corbel by bonding CFRF. Eur J Environ Civ Eng. 2020;24(12):1993-2009. <https://doi.org/10.1080/19648189.2018.1496229>
- [122] Ghazani OS, Moghadasi M, Taeepoor S. Numerical study of reinforced concrete corbels with different layup schemes of CFRP laminates. J Teknol. 2022;84(1):171-181. <https://doi.org/10.11113/jurnalteknologi.v84.17066>
- [123] Al-Kaabi NH, Al-Thairy H, Abo Dhaheer MS. Behavior of reinforced concrete corbels strengthened by FRP composites and steel bars: a critical review. IOP Conf Ser Earth Environ Sci. 2023;1232(1):012035. <https://doi.org/10.1088/1755-1315/1232/1/012035>
- [124] Al-Kaabi NH, Al-Thairy H, Abo Dhaheer MS. Behavior of reinforced self-compacting recycled concrete corbels strengthened with NSM GFRP bars. J Build Pathol Rehabil. 2024;9(1):19. <https://doi.org/10.1007/s41024-023-00366-2>
- [125] Shakir QM, Kamonna HHH. The behavior of high strength self-compacting reinforced concrete corbels strengthened with NSM steel bars. Int J Adv Sci Eng Inf Technol. 2018;8(4):1022-1028. <https://doi.org/10.18517/ijaseit.8.4.5208>
- [126] Ali AY, Abbas AAA. Structural behavior of reinforced lightweight concrete corbels strengthened with NSM-CFRP bars. Int J Civ Eng Technol. 2016;7(4):380-392.
- [127] Abdul-Alhassan SM, Kadhim MJ. Analysis of reinforced concrete brackets strengthened with steel fiber. J Phys Conf Ser. 2021;1973(1):012219. <https://doi.org/10.1088/1742-6596/1973/1/012219>
- [128] Campione G, Cannella F. Analytical model for flexural response of reinforced concrete corbels externally strengthened with fiber-reinforced polymer. ACI Struct J. 2020;117(4):91-102. <https://doi.org/10.14359/51724629>
- [129] Abbas MK, Hamzah MK, Naser ZA, Al-Salim NH. Torsional performance of reinforced concrete beams strengthened with high-performance concrete: numerical analysis. J Eng Sustain Dev. 2026;30(1):45-58. <https://doi.org/10.31272/jeasd.30.1.4>
- [130] Abbas MK, Hamzah MK. Numerical investigation on flexural performance of hybrid concrete T-beams. In: Proceedings of the International Conference on Structural Engineering and Construction; 2023.
- [131] Russo G, Venir R, Pauletta M, Somma G. Reinforced concrete corbels - shear strength model and design formula. ACI Struct J. 2006;103(6):904-906. <https://doi.org/10.14359/18244>
- [132] Han B, Huang Y. Shear test on concrete corbels: ACI 318-19 formulas evaluation. ACI Struct J. 2024;121(3):3-14. <https://doi.org/10.14359/51740597>
- [133] Abdul-Razzaq KS, Dawood AA, Jalil AM. Analysis and design of RC wide corbels - suggested procedure. AIP Conf Proc. 2020;2213(1):020161. <https://doi.org/10.1063/5.0000167>
- [134] European Committee for Standardization. EN 1992-1-1: Eurocode 2: Design of Concrete Structures - Part 1-1: General Rules and Rules for Buildings. Brussels: CEN; 2004.
- [135] Schlaich J, Schäfer K, Jennewein M. Toward a consistent design of structural concrete. PCI J. 1987;32(3):74-150. <https://doi.org/10.15554/pcij.05011987.74.150>
- [136] Bayrak O, Hrynyk ST. Investigation of corbels designed according to strut-and-tie and empirical methods [doctoral dissertation]. Austin (TX): University of Texas at Austin; 2017.

- [137] Abdul-Razzaq KS, Dawood AA. Reinforcing struts and ties in concrete corbels. *ACI Struct J*. 2021;118(4):153-162. <https://doi.org/10.14359/51730538>
- [138] Yun YM, Lee Y. Strengths of struts and nodal zones for strut-and-tie model design of reinforced concrete corbels. *Civ Eng J*. 2021;7(8):1275-1289. <https://doi.org/10.28991/CEJ-2021-03951722>
- [139] Allen MN, El-Salakawy EF. Investigation of strut-and-tie model performance using symmetrically loaded GFRP-RC double corbels. *J Compos Constr*. 2024;28(5):04024037. <https://doi.org/10.1061/ICCOF2.CCENG-4632>
- [140] Yun YM, Chae HS. An optimum indeterminate strut-and-tie model for reinforced concrete corbels. *Adv Struct Eng*. 2019;22(12):2557-2571. <https://doi.org/10.1177/1369433219846957>
- [141] Yun YM. Numerical method for the strength of two-dimensional concrete struts. *Comput Concr*. 2021;28(6):621-634. <https://doi.org/10.12989/cac.2021.28.6.621>
- [142] Huang Y, Han B, Yin W. Reinforced concrete corbels shear test: the triangular-truss method evaluation. *Buildings*. 2022;12(10):1619. <https://doi.org/10.3390/buildings12101619>
- [143] Nguyen PD, Le TA, Dang VH. A probabilistic model for predicting the shear capacity of reinforced concrete corbels based on an enhanced interactive strut-and-tie model. *Structures*. 2026;87:111745. <https://doi.org/10.1016/j.istruc.2025.111745>
- [144] Megahed K. STM-based symbolic regression for strength prediction of RC deep beams and corbels. *Sci Rep*. 2024;14(1):25066. <https://doi.org/10.1038/s41598-024-76292-1>
- [145] Abbas MK, Ali AY. Machine-learning prediction of shear capacity of RC corbels under combined vertical and horizontal loading. *Al-Noor J Eng Manag Comput Sci*. 2026;4(1):15-28. <https://doi.org/10.5281/zenodo.1089234>
- [146] Abbas MK, Harith IK. Deep beam shear prediction via K-fold cross-validated stepwise regression and a graphical user interface: a comparative analysis with state-of-the-art models. *Asian J Civ Eng*. 2025;26(2):415-430. <https://doi.org/10.1007/s42107-024-01180-2>