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Reinforced Concrete Deep Beams: Review of Load Transfer Mechanisms, Shear Behaviour, Analytical Models, and Design

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Abstract: Deep beams in reinforced concrete (RC) are important load-carrying elements in the design of transfer girders in tall structures, pile caps, and offshore structures. Unlike slender beams, their small span-to-depth ratios make their strain distributions non-linear, so flexure is no longer the dominant failure mode, and shear becomes the most important. Within the last few decades, research has shifted from the classical beam theory to the concept of strut-and-tie models (STM) and the mechanics of arch action, which explain the actual manner in which loads are carried by these members. This paper reviews this development systematically. It addresses the shear span-to-depth ratio (a/d), size effect, the concrete compressive strength, and web reinforcement system arrangement as the primary controlling parameters before comparing the classical empirical expressions with the available analytical models, code provisions, and data-driven/machine learning predictions. At the end of the review, the gaps in design standards are emphasized, and topics are suggested for future experimental and analytical research.

1. Introduction

RC deep beams are utilized in the application of heavy loads being transmitted across relatively short spans, such as the transfer girders in high-rise structures, pile caps, foundation mats, and bridge diaphragms [1], [2]. The limits control their response, and they are defined by a shear span-to-depth ratio of at most 2.0 ($a/d \leq 2.0$) or a clear span-to-overall depth ratio of at most 4.0 ($L/d \leq 4.0$). In a slender beam, flexure is the mode of deformation, and the strains are linear throughout the depth of the beam. A deep beam does not have distinct shear deformation; it has non-linear strain profiles [3], [4]. The Bernoulli–Euler theory is therefore inapplicable, and the member is considered to be a discontinuity region (D-region) that carries the load primarily by direct arch action. [5], [6].

The design of these regions rests on the truss analogy. Truss-based tools for beam design were developed during the 1980s [7], and Schlaich [8] turned them into a consistent framework for structural concrete that became the basis of the strut-and-tie approach used today. Shear in cracked concrete has also been approached from the continuum side: the modified compression field theory of Vecchio and Collins [9] describes the response of cracked reinforced concrete elements subjected to shear, and kinematic models for deep beams draw on this line of thinking [10].effects, and web reinforcement distribution [11]. Strut and Tie Modeling (STM), as represented by standard design codes like ACI 318 and Eurocode 2, has conceptualized these internal stress fields, but there are significant differences in the efficiency factors for the struts and web reinforcement provisions. [12].

A sound understanding of shear behavior and load paths is a prerequisite for designing deep beams that are both safe and economical. Most of the force travels along inclined concrete compression struts that run from the loading points to the supports, with the longitudinal reinforcement acting as a tie [13]. Estimating ultimate shear strength is nonetheless difficult. Shear failure is brittle, and the

response depends on interacting factors such as multi-axial stress states, tensile cracking of the concrete, size effect and the distribution of web reinforcement [14]. ACI 318 and Eurocode 2 both adopt the strut-and-tie method (STM) to represent the internal stress fields, but they still disagree on strut efficiency factors and on how much web reinforcement is required. effects, and web reinforcement distribution. Standard design codes, such as ACI 318 and Eurocode 2, have adopted Strut-and-Tie Modeling (STM) to conceptualize these internal stress fields, yet notable variations persist regarding strut efficiency factors and web reinforcement requirements. effects, and web reinforcement distribution. Standard design codes, such as ACI 318 and Eurocode 2, have adopted Strut-and-Tie Modeling (STM) to conceptualize these internal stress fields, yet notable variations persist regarding strut efficiency factors and web reinforcement requirements.

Because empirical code equations are often conservative and limited, attention has recently turned to mechanics-based formulations and to data-driven machine learning (ML) models [15], [16]. Even so, no systematic comparison yet places conventional STM, kinematic models and interpretable AI approaches side by side, and such a comparison is needed to show where the field stands and where gaps remain. This review addresses that need by evaluating the current literature on RC deep beams. It examines the mechanics of direct arch action, the parameters that govern shear strength, the analytical models and code provisions in use, and the recently proposed ML models, and it closes with suggestions for future research.

2. Load Transfer Mechanisms and Key Parameters

2.1 Arch Action vs. Beam Action

Two internal mechanisms, beam action and arch action, jointly determine how an RC deep beam responds. In slender members, shear is carried mainly by beam action, which draws on tensile stresses in the longitudinal steel, aggregate interlock along shear cracks and dowel action.

In deep beams (generally $a/d \leq 2.0$) this picture changes once diagonal cracks form. Load then passes straight from the loading point to the support through an inclined compressive strut, a mechanism known as arch action. Chen point out that, in continuous deep beams, compressive struts that continue over interior supports are central to load distribution and alter the redistribution of moment and shear relative to ordinary flexural members.

2.2 Shear Span-to-Depth Ratio (a/d)

The effect of the shear span-to-depth ratio (a/d) on the failure mechanism and ultimate shear capacity of RC deep beams is generally considered to be the most significant among the parameters.

For $a/d > 2.5$, the member is virtually a thin beam, and therefore fails in flexure or by classic diagonal tension.

If $1.0 < a/d < 2.5$, the member starts to clearly enter into arch action; failure will now be shear compression or crushing of the diagonal strut.

When a/d is between 0 and 1.0, the arch action dominates, and direct compressive load transfer provides substantially greater shear capacities.

Interpretable machine learning and other data-driven studies have repeatedly shown that a/d is the most important geometric or material property of the shear, in terms of its importance in predicting shear capacity.

2.3 Size Effect in RC Deep Beams

Non-linear reduction of the nominal shear strength with the overall depth (d) is termed the size effect, even if material properties and reinforcement ratios remain constant.

In the case of simply supported RC deep beams, Chen analyzed the shear size effect and concluded that the shear strength of deeper beams drops at lower normalized shear strength and failure

mechanism is more brittle. They attributed this to the failure being preceded by wider cracks, and therefore more energy is released.

Previous experiments corroborate this. Tan and Lu [17] tested large deep beams and concluded that the ultimate shear stress is a function of member size, the best representation of which is provided by the size-effect law proposed by Bažant, and that larger beams failed more brittlely. Later, Zhang and Tan [18] pointed out that the geometry of struts and boundary conditions are the principal causes: They found that the size effect on ultimate shear strength is significantly reduced when suitable loading and support plate dimensions are used, and that web reinforcement is beneficial but not significant. Tan [19] observed likewise, because beams with no web reinforcement lost strength rapidly with size, whereas another set of beams had strengths that were independent of size. In the case of continuous deep beams, Yang [20] noted that the effects of depth were more pronounced than in simply supported beams, and were more pronounced for higher-strength concrete and web reinforcement distribution. Standard design codes, such as ACI 318 and Eurocode 2, have adopted Strut-and-Tie Modeling (STM) to conceptualize these internal stress fields, yet notable variations persist regarding strut efficiency factors and web reinforcement requirements.

Li et tested how member depth and concrete strength affect deep beams without transverse reinforcement. Their results showed that a greater section depth, if not accompanied by adequate web reinforcement, leads to a marked loss of strength. Design formulas that contain no explicit size-effect factor may therefore be unconservative for large deep beams.

2.4 Influence of Web Reinforcement and Concrete Strength

Web reinforcement in a deep beam consists of vertical stirrups and horizontal reinforcement, and has a few different functions:

1. Crack control: it restricts the width of early diagonal tension cracks and so helps retain aggregate interlock.
2. Strut confinement: It restrains the lateral movement of the main compressive strut and thereby increases the crushing strength of the concrete.

Kondalraj and Rao have conducted tests on deep beams of various layouts of horizontal and vertical bar reinforcements, and concluded that an even distribution of horizontal and vertical bar reinforcement is observed to have a significant effect on improving the efficiency of the strut in compression. They also noted that higher concrete compressive strength (f'c) increases load capacity, but without enough web steel it leads to steeper and more abrupt diagonal shear failure planes.

3. Analytical Models and Strut-and-Tie Modeling (STM)

3.1 Principles of the Strut-and-Tie Method

The strut-and-tie model (STM) is a lower-bound limit analysis approach that design codes such as ACI 318-19 and Eurocode 2 recommend for D-regions of RC structures.

An RC deep beam has a complex internal stress field, which is replaced by an equivalent truss containing three types of components in STM.

1. Struts: inclined or vertical concrete compression members that stand for zones of high compressive stress.
2. Ties: tension members – the key longitudinal reinforcement.
3. Nodes: areas of struts, ties, and external loads or reactions, and are categorised as C-C-C (struts/struts/external load), C-C-T (struts/ties/external load), and C-T-T (struts/ties/struts).

Abbood and Kalantari and Kianoush both note that STM gives an intuitive physical picture for shear design, yet in practice it is difficult to select the strut efficiency factor (βs) accurately and to define node geometry.

The present form of the method goes back to Schlaich. Brown and Bayrak [21] assembled a database of deep beam tests, compared several truss models through strain energy, and found that a single direct strut between the load and one support was the most favorable mechanism; they then evaluated the STM provisions of ACI 318-05 and AASHTO LRFD against the database. Tuchscherer [22] reached a similar verdict for ACI 318-08 and AASHTO LRFD (2008), describing them as overly conservative, and proposed a simpler procedure based largely on fib provisions that is more accurate while remaining just as conservative. effects, and web reinforcement distribution. Standard design codes, such as ACI 318 and Eurocode 2, have adopted Strut-and-Tie Modeling (STM) to conceptualize these internal stress fields, yet notable variations persist regarding strut efficiency factors and web reinforcement requirements.

3.2 Advancements in Modified and Interactive STMs

Several researchers have proposed refined STM formulations to overcome the empirical limits of standard code expressions:

Liu & Mihaylov compared the ACI STM provisions to kinematic shear models, and concluded that models derived from the concept of crack kinematics are more consistent with the ACI STM provisions than are simplified empirical stress limits.

Liu & Mihaylov compared kinematic shear models with the ACI STM provisions and found that models based on crack kinematics are more consistent than simplified empirical stress limits.

Chetchotisak developed a modified interactive STM that captures the ongoing interaction between softening of compressed concrete and yielding of steel in deep beams and corbels.

Kondalraj & Rao assessed the ACI 318-19 provisions and proposed an improved strut coefficient that includes web reinforcement density, which raises safety margins in heavily reinforced deep beams.

Mihaylov proposed a two-parameter kinematic theory (2PKT) which stipulates the deformed shape of a deep beam with two main parameters. With equilibrium equations and stress-strain relationships, it predicts shear strength, crack widths, maximum deflection and the displacement field, and it captures a size effect even in beams with transverse reinforcement. The theory was validated against a large number of experimental results.

4. Modern Data-Driven and Machine Learning Approaches

4.1 Emergence of Artificial Intelligence in Structural Engineering

Current design standards are based on empirical equations and conventional STM; these exhibit significant scatter in comparison to large experimental databases. The scatter arises mainly from non-linear interactions among geometric and material variables, including aggregate interlock across cracks, strong concrete softening and multiaxial stress fields.

Several data-driven algorithms and sophisticated machine learning (ML) techniques have been used to circumvent these simplifications. They are not based on idealized models; therefore, they can explain the ultimate shear behavior of RC deep beams with high accuracy.

4.2 Application of ML Algorithms and Reliability Analysis

Recent studies have also integrated machine learning with structural reliability frameworks to complement or improve current design provisions.

Shahnewaz refined the expressions for the shear strength through a genetic algorithm (GA) which was calibrated with a huge data set of deep beam tests. Together with an extensive reliability analysis, the GA-based model significantly lowered the scatter of the safety level, and it was consistent across both section sizes and concrete grades.

Ma built an interpretable ML framework that couples XGBoost with SHAP (SHapley Additive exPlanations) to predict shear capacity. Unlike black-box predictors, it exposes how each input contributes physically, and it confirmed a/d and concrete compressive strength (f′c) as the dominant

variables for ultimate shear capacity. confirming that the shear span-to-depth ratio (a/d) and concrete compressive strength (f'c) exert the most dominant influence on ultimate shear capacity. confirming that the shear span-to-depth ratio (a/d) and concrete compressive strength (f'c) exert the most dominant influence on ultimate shear capacity.

Abbas and Albidah carried out a data-driven study of several advanced ML algorithms for predicting shear failure of deep beams. Optimized models reached excellent accuracy ($R^2 > 0.95$) and a much lower coefficient of variation than design provisions such as ACI 318-19 and Eurocode 2.

5. Critical Comparison and Research Gaps

5.1 Comparative Summary of Current Methodologies

Comparing current analytical and predictive approaches shows clear differences between international design standards, mechanics-based formulations and modern data-driven methods.

Code provisions (e.g., ACI 318-19, Eurocode 2): give simplified STM guidance that favors safety and ease of use. They tend to be conservative on shear strength, however, and do not fully reflect size-effect degradation or interactions with web reinforcement.

Advanced mechanical and kinematic models: capture crack kinematics and the distribution of forces in arch action. They give clearer insight into local crushing and tensile yielding, but usually need iterative calculation.

Data-driven and ML frameworks: provide the best numerical accuracy ($R^2 > 0.95$) and markedly less scatter over wide experimental ranges. Their main difficulty is converting these statistical predictions into simple, code-style design equations without losing physical interpretability.

5.2 Identified Research Gaps

Despite steady progress in understanding the shear behavior of RC deep beams, the literature still has several important gaps:

1. Hybrid physics–AI modeling: current ML models act mostly as statistical predictors. Few hybrid models build physical constraints, such as equilibrium and strain compatibility in STM frameworks, directly into the ML architecture.
2. Size effect in sustainable concrete: size effect in conventional deep beams is well documented, but few analytical models consider how member depth (d) combines with alternative sustainable materials, such as recycled aggregates or alkali-activated concrete, in softening the diagonal strut.
3. Cyclic and dynamic loading: most database records come from monotonic static tests. Better analytical and numerical models are required to predict loss of shear capacity under fatigue, seismic or reversed cyclic loading.

5.3 Synthesis and Practical Implications

The strength and deformation properties are reproduced by kinematic theory, but the calculations are more complex, including the size effect. Machine learning yields the lowest scatter, but the predictions cannot be directly incorporated into the design equations. A hybrid approach, in which kinematic or STM relations are used to force a data-driven model, thus appears to be the most promising approach to combine accuracy with transparency effects and web reinforcement distribution. Incorporation of these internal stress fields has been adopted in standard design codes including ACI 318 and Eurocode 2, but there are significant differences in the efficiency factors used for struts and the recommendations for web reinforcement.

The size-effect literature also carries a practical message. Because strut geometry, plate dimensions and web reinforcement all influence how strength falls with depth, a design factor that depends on depth alone is unlikely to be sufficient. Designers should treat bearing plate size and web reinforcement layout as design variables of the strut, not as detailing afterthoughts. effects, and web

reinforcement distribution. Standard design codes, such as ACI 318 and Eurocode 2, have adopted Strut-and-Tie Modeling (STM) to conceptualize these internal stress fields, yet notable variations persist regarding strut efficiency factors and web reinforcement requirements.

6. Results and Discussion

Influence of Shear Span-to-Depth Ratio on Shear Behaviour

The reviewed literature indicates that the shear span-to-depth ratio (a/d) is one of the most influential parameters governing the structural behaviour and ultimate shear capacity of reinforced concrete deep beams. As the a/d ratio decreases, the contribution of direct arch action becomes increasingly significant, allowing compressive forces to transfer directly from the loading points to the supports. This behaviour distinguishes deep beams from conventional slender beams, where flexural and beam-action mechanisms play a more dominant role. The findings reported in previous analytical and experimental studies confirm that the internal load-transfer mechanism changes considerably with variations in a/d. In particular, beams with lower a/d ratios generally exhibit higher shear resistance due to the formation of direct compression struts. However, this increased resistance is associated with a greater possibility of diagonal strut crushing and localised compression failure.

The comparative evidence also suggests that conventional design equations may not adequately represent the complex interaction between arch action, diagonal cracking and reinforcement behaviour across different a/d ratios. Therefore, the accurate identification of the governing load-transfer mechanism is essential for improving the reliability of deep-beam design.

7. Conclusions

The following main conclusions follow from this review of recent experimental, analytical and data-driven work on RC deep beams: Dominance of arch action: when $a/d \leq 2.0$, direct compressive arch action is the main load-transfer mechanism, carrying forces straight to the supports and leading to shear-compression failure. Size effect on shear capacity: Member depth (d) has a significant size effect. When no increase in transverse reinforcement is provided with depth, the nominal shear strength decreases with depth, so it is necessary for the design provisions to explicitly incorporate the size effect factors. Refinement of STM: Standard STM is an intuitive tool for D-region design, but accuracy can be significantly improved if strut efficiency factors (βs) take into account multi-axial strain states and web reinforcement. Good predictive capability of ML: The advanced ML methods like XGBoost and GA optimized models have higher correlation ($R^2 > 0.95$) and have identified a/d and f′c as the key governing parameters. Size effect and strut geometry: Strength reduction due to increasing depth is not strictly proportional to the depth, but also to the geometry of the struts and dimensions of the plates and web reinforcement should be taken into account in design provisions, not the depth alone.

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