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Shear Behaviour in Reinforced Concrete Beams (Mechanisms, Failure Modes, and Predictive Models): A Review

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ABSTRACT

Shear failure in reinforced concrete beams is considered a significant challenge due to its unpredictable nature and severe consequences. This review aims to study the shear behaviour and design prediction for reinforced concrete beams by conducting a comprehensive analysis of previous studies that have investigated the shear behaviour of reinforced concrete beams. The review examines shear mechanisms and their effects on reinforced concrete beams. It specifically focuses on the influence of aggregate interlock, dowel action, and arch action on the shear behaviour of these beams. In addition, the paper discusses cutting-edge testing methodologies and simulation modelling, such as digital image correlation and analytical models, that provide a more profound understanding of shear transfer activities and failure modes. The research also highlights the key elements that substantially impact shear behaviour, including longitudinal reinforcement, shear span-to-depth ratio (a/d), and beam size. The research analysed the advantages and disadvantages of current researches, highlighted areas where knowledge is lacking, and evaluated some design code predictions.

1. Introduction

One of the most critical failures of the reinforced concrete beam occurs in shear, which can be sudden and catastrophic, causing significant damage without much warning. Unfortunately, there is no opportunity for stress redistribution in these situations. Structural engineers must pay close attention to shear failures as they can be extremely dangerous. It is crucial to design structures in a way that minimizes the risk of sudden shear failures[1].

The shear strength accuracy influenced by approximately 20 variables, which was one of the main reasons for the deficient quality of the design provisions for shear and torsion. Another contributing factor was the fact that a significant number of the experimental results that were available were either impractical or of low quality [2]. The forces imposed in a direction perpendicular to the longitudinal axis of structural elements are referred to as shear forces. The presence of a single diagonal crack or a sequence of diagonal cracks oriented at an angle mostly (45◦ degrees) to the axis of the beam indicates a shear failure. Shear failure may alternatively be defined as diagonal tension failure, where diagonal cracks emerge due to the presence of diagonal tension within the reinforced concrete beam [3]. The shear behavior of the reinforced concrete beams is very complex and can be affected by a lot of factors, including the compressive strength of concrete (fc'), the shear span to the depth ratio (a/d), the amount of the longitudinal reinforcement (ρw), size effect, the width of the crack and the presence of shear

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reinforcement [4]. As a result, the shear prediction procedure design is based on empirical equations. Therefore, the researchers continuously have been trying to develop and enhance the shear design equations in different concrete codes worldwide, and using transverse reinforcement in shear can be effective but may only sometimes be efficient. Factors such as: cost-effectiveness, ease of construction, and sustainability can sometimes result in the construction of structural components that do not require additional support to withstand shear forces across the entire depth of the concrete. This design is frequently used in some structures, such as bridges, tunnels, frame buildings, and foundation elements [5] to [9].

2. Shear failure in reinforced concrete beams

Shear failure in reinforced concrete beams is undesirable due to its sudden and brittle nature, providing minimal warning compared to the significant deflection seen in flexural failures of under-reinforced beams. While flexural failure loads are straightforward to calculate and consistently addressed in design codes, shear failure predictions using empirical equations are often inadequate. Thus, it is crucial to understand and explain failure patterns. Five distinct shear failure mechanisms have been identified based on beam dimensions, configurations, applied loads, longitudinal reinforcement, and concrete properties: diagonal tension failure, shear compression failure, tension shear failure, web crushing failure, and arch rib failure[10][11], as shown in Figure 1. in case of slender beams without stirrups where shear -span to depth ratio a/d>2.5, an inclined tensile cracking developed perpendicular to the tensile stress when these stresses exceed the tensile strength of concrete[12]. Taylor 1960) [13], indicated that, this cracking stage is not defined sufficiently in the experimental test of beams gradually and so rapid and sensitive, while identification for this crack based on the judge of the observer. The ongoing studies on beams because the cracks propagated near the applied loads.

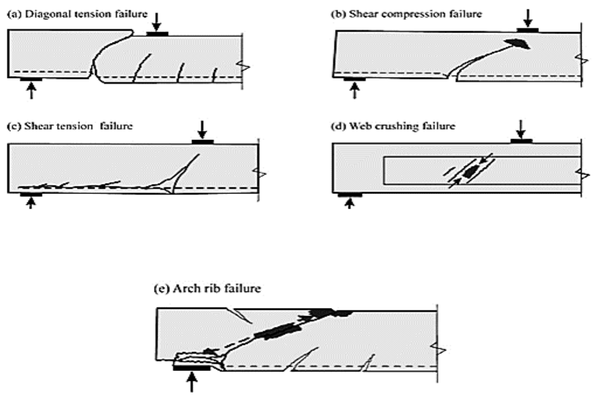

Figure 1. Shear failure modes[11]

In beams without stirrups, the ratio between the shear force causing inclined cracking and the observed shear strength varies between (0.74 to 0.97) and is highly unpredictable. Hence, accurately determining the diagonal tensile strength and cracking load in a reinforced concrete beam is challenging due to the need for precise knowledge about the distributions of shear and flexural stresses. In addition, the load at which cracks begin to form is not directly proportional to the load at which failure occurs. The crack initiation load can be significantly smaller or only slightly smaller, depending on the size of the beam and other parameters [14][15].

Krassowska, (2003) [16] focused on monitoring the variations in beam behaviour with different levels of shear reinforcement and fibre content. the study investigated two-span beams, with dimensions of (80 x180) mm and a length of 2000 mm, by subjecting them under tests with varying stirrup spacings. Steel fibres quantities as: 78.5 kg/m^3 (1.0%) and 118 kg/m^3 (1.5%) were employed, alongside with plain concrete beams. The beams were subjected to a five-point bending test until failure, evaluating either shear or bending capacity as shown in Figure 2. Fiber-reinforced concrete beams retained their form under load and displayed more, albeit narrower, diagonal cracks compared to the sudden, brittle failure of regular concrete beams. Steel fibres notably enhanced shear stress, and the post-cracking by showing more crack as a warning before the failure as shown in Figure 2. (a), in contrast to plain concrete which was more sudden as shown (b).

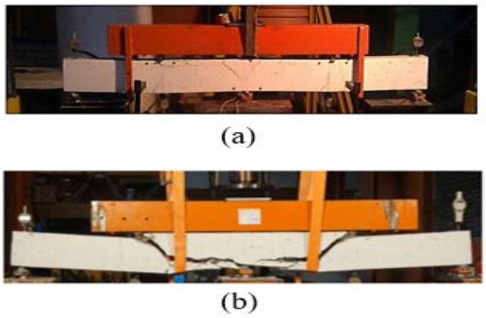

Figure 2. Specimens testing [16]

Mak and Lee, (2003) [17] investigated the effectiveness of arch action in shear-critical reinforced concrete beams by testing six specimens different in geometry as shown in Figure 3. This approach of change in geometry has increased shear resistance by 62% to 122% and enhanced ductility and deformability. Also, it delayed cracking and increased midspan deflections in the modified specimens, indicating improved performance better than the prismatic reference beam. The study proposed a kinematic-driven structural philosophy, aligning static and kinematic quantities for enhanced structural compliance and mobilized ductility without internal stress redistribution. These findings had significant implications for assessing existing structures and designing more efficient new ones, offering a promising approach to improving reinforced concrete beam performance.

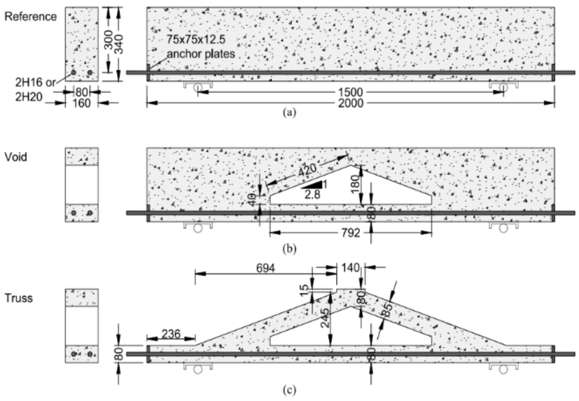

Figure 3. Geometry of the specimens, (a) Reference; (b) Void; (c) Truss [17]

Nakamura et al., (2018) [18] evaluated shear resistance or reinforced concrete beams and failure modes, including arch and beam actions, showing that shear strength can be assessed without distinguishing between deep and slender beams. Also, the study compared the test results with simulation distribution of stress. They concluded that shear strength of reinforced concrete beams can be evaluated without classification of deep beams and slender beams. Kim et al., (2021) [19] suggested new method for designing prestressed concrete beams focuses on the concrete's compression zone to predict strength. This method, similar to current design approaches, shows improved accuracy compared to existing methods and better reflects how design factors influence beam strength.

3. **Mechanisms of shear strength transfer in reinforced concrete beams**

Shear stress is transmitted from one plane to another plane in various ways in reinforced concrete members. The transfer mechanisms of the forces in cracked section of reinforced concrete beams subjected to shear stress are defined by ACI-ASCE Committee report 426 [20]. Figure 4. shows the shear transfer actions; uncracked Concrete Compression Zone (Vcc), the residual tensile stress in the concrete (V_{CR}), Dowel Action (V_d), Aggregate Interlock (V_{AI}) and the arch action (V_{ARC}) which is related to the theoretical strut action of the beam. When concrete cracks under tensile loading, crack interfaces can experience significant slip deformation due to the applied crack kinematics. As slip occurs along these crack interfaces, aggregate interlock stresses are generated. These stresses transfer shear and normal forces. As cracks widen, aggregates interlock shear resistance (V_{AI}) decreases while the dowel action (V_d) increases the shear transfer and the compression zone shear action (Vc). Aggregate interlock failure leads to a large shear force transfer to the compression zone, hence the sudden failure [1], [21] to [23]. The dowel action (Vd) is a well-known phenomenon in which longitudinal reinforcement contributes to shear transfer. However, the effect is more obvious in reinforced concrete beams without shear reinforcement than in beams with stirrups.

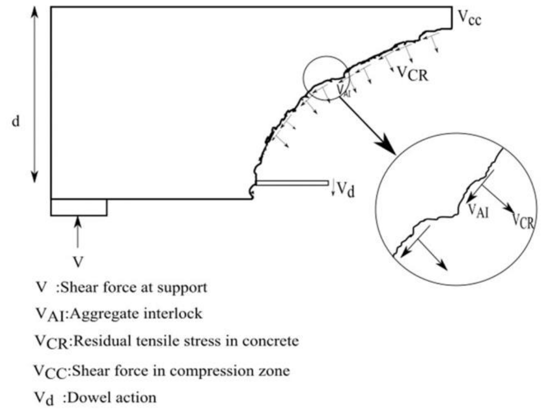

Figure 4. Shear transfer mechanisms in reinforced concrete [1]

The Arch Action in flexure-shear interaction, when the shear span to depth ratio (a/d) is small, the arch action contributes more than the beam action, like deep beams [24].

El-ariss, (2007) [25] presented a simple analytical model for the dowel action of reinforcing bars crossing cracks in concrete. The model is integrated into a computer program to analyse reinforced concrete beams nonlinearly. The behaviour of the dowel bar is determined by the theory of a beam on an elastic foundation. El-ariss made a parametric study to examine how various factors, such as bar diameters and the amount of reinforcement, affect the dowel action as a shear transfer mechanism across cracks. Also, the study was conducted with other experimental results for a more comprehensive and gratifying outcome. The result of the study showed that the model successfully predicted the behaviour of shear behaviour in critical reinforced concrete members, and the dowel action significantly impacts the behaviour and ductility of reinforced concrete beams, particularly in cases where the amount of web reinforcement is low. The researcher recommended Additional research to gain a deeper understanding of the significance of dowel action in concrete structures.

Zakaria et al., (2009) [26] experimentally studied 10 simply supported beam specimens to investigate the shear cracking behaviour, by study the several variables affecting the shear behaviour {shear span to depth ratio (a/d), concrete cover, stirrups, loading conditions, and the longitudinal reinforcement ratio}. Regarding the effects of longitudinal reinforcement, the results revealed that augmenting the quantity of longitudinal reinforcement enhances control over the opening of shear cracks near the longitudinal reinforcement. This implies that the shear cracking mechanism is significantly influenced by the ratio of longitudinal reinforcement. They found the increase in the amount of longitudinal reinforcement results in reduced spacings between shear cracks, leading to smaller width of shear crack. The study explained the behaviour, by presuming this phenomenon can be attributed to the enhanced bond effect between the longitudinal reinforcement and the adjacent concrete, which improves crack control characteristics and diminishes crack spacing. Furthermore, a larger quantity of longitudinal reinforcement effectively curbs the growth of flexural cracks and prevents their transformation into flexure-shear cracks.

Moradi et al., (2012) [27] Developed a simplified constitutive model for dowel action in reinforced concrete beams. The study extends the Beam on Elastic Foundation (BEF) analogy by including an elasto-plastic formulation for subgrade springs. Also, Moradi et al. conducted an experimental program that involved testing five beam-type specimens with cyclic and repeating loading conditions to simulate seismic stresses. Key findings include; the relative significance of various shear-transfer actions, stiffness degradation under cyclic loading, and the dominance of dowel action as cracks widen.

The proposed model was calibrated and verified using experimental data, showing good agreement with observed behaviour. Significant stiffness degradation and pinching effects in load-displacement curves were noted. The study also provided empirical equations for stiffness degradation and load-displacement response, validated against experimental data. The research highlighted the importance of considering dowel action in structural analysis and design, contributing valuable insights for predicting the performance of reinforced concrete structures under seismic conditions.

Samad et al., (2016) [28] tested two simply supported reinforced concrete T-beams (1500 x 150 x 300) mm with a flange size of (300 x 120) mm, to investigate the shear mechanism and the shear strength prediction. The beams were subjected to a four-point bending test until failure. Both beams were designed based on the specifications of ACI318-08 and Eurocode2 (EC2), with identical parameters, including a longitudinal reinforcement ratio (0.0215) and a shear span-to-depth ratio (av/d) of 3.5. The concrete characteristic compressive strength was targeted at (35 – 40) N/mm²; BEAM1 was constructed according to ACI318-08, while BEAM2 followed EC2 guidelines. The specifications, load, and deflection at failure for each specimen were documented, indicating the performance differences between the two design codes. Both beams were designed to fail in shear, with the critical shear cracks exhibiting diagonal tension crack failure. The results indicated that while ACI318-08 provided a more simplified approach, EC2's predictions were slightly higher in the shear strength prediction. Also, the flexural cracks appeared first at mid-span before shear cracks developed and spread to the flange areas at both ends. In general, ACI318-08 and EC2 provide different specifications; both codes offer effective and reasonable methods for predicting concrete shear strength.

Cavagnis et al., (2018) [29], Conducted a series of tests on reinforced concrete beams without shear reinforcement to analyze the shear transfer actions in reinforced concrete beams based on experimental findings. The experimental program involved 24 tests on 20 beams. Digital image correlation was utilized in the experimental program during the loading process. The measurements obtained through digital image correlation provided a clear understanding of the transfer of forces between different potential shear-carrying actions as the beams underwent loading. This technology allowed for tracking the displacement, cracks, and the forces transfer for understanding the shear failure process. The specimens were examined through various loading and support conditions such as simply supported, continuous, and cantilever beams; all beams were subjected to distributed and one-point loads. The beams had the same cross-section with different lengths, two longitudinal reinforcement ratios (0.0054٤ and 0.008٨٦), a maximum aggregate size of 16 mm, and a compressive strength of concrete ranging from 31.2 to 36.9 MPa. They found Variations in Shear-Transfer Actions with the shape and position of cracks. As loading progresses and cracks develop, some shear-transfer mechanisms become more significant while others diminish. Also, for slender beams, the shear force is predominantly supported by aggregate interlock, dowel action, and the residual tensile strength of concrete, but aggregate interlock is the most dominant shear transfer action. Arching action becomes the primary shear-transfer mechanism only when the critical shear crack develops below the intermediate support in the continuous beams when the a/d is low in the deep members.

Christiano and Makarim, (2021) [30] Conducted an experimental study to investigate the impact of longitudinal reinforcement on the shear capacity of concrete beams. They did not add coarse aggregate to the concrete for the aggregates interlock action; marble powder and increased fine aggregates amount used instead; they tested six beams without shear reinforcement by two points loading; a/d was 4.285, and the longitudinal reinforcement ratios are (0.0077, 0.0137, 0.214, 0.0308, 0.0547, and 0.0772) maximum. The findings revealed a significant correlation between the longitudinal reinforcement ratio and the shear strength capacity ratio (Vu/Vc) of concrete beams, specifically. As the longitudinal reinforcement ratio increases, so does the shear strength capacity of the concrete beam. Notably, the shear strength capacity of a beam with the highest longitudinal reinforcement ratio is approximately 82% greater than that of a beam with the lowest ratio. Also, they found that the application of the ACI shear equation is accepted when the reinforcement ratio approaches the maximum.

Trindade et al., (2023) [31], Examined the shear behavior of reinforced concrete with Recycled Aggregate Concrete (RAC) beams. Twelve reinforced concrete beams, six with natural aggregate concrete and six with 100% recycled coarse, were tested under four-point load setup. The beams had the same compressive strength (38 MPa) and same ratio of cement and aggregates per volume, but varied in longitudinal and transverse reinforcement ratios. The researchers found a 28% average reduction in the shear strength of recycled aggregate concrete beams with no stirrups compared to Natural aggregate concrete beams. However, beams with stirrups showed similar shear strength, regardless of the aggregate type. This was attributed to the evaluation of shear transfer mechanisms, which revealed that aggregate interlock was the primary resistance mechanism throughout the test of beams without stirrups. The results were also compared with those predicted in design codes. The codes were conservative for beams with stirrups and less accurate than those obtained by the shear transfer mechanisms. The study concludes that in the presence of transverse reinforcement, the shear strength predicted by the sum of shear transfer action was closer to the experimental result than those predicted by design codes.

Autrup et al., (20230 [32] investigated the shear transfer action of the tensile reinforcement (dowel action) for a reinforced beam without shear reinforcement by adopting a novel experimental test for 34 specimens of reinforced concrete beams, as shown in Figure 5. The specimens were constructed of two distinct pieces, a top section and a lower half, which were only attached by the longitudinal reinforcement at the pre-made cracks. Two rebars were used to cross the pre-made crack in the lower section of the structure, which served as the longitudinal reinforcement. They used digital image correlation (DIC) as measuring system with displacement and the structural behavior. When the specimens were tested, the findings of this investigation are:

- Because inclined- and horizontal cracks began to form before any dowel force was applied, the shear-transfer action of activated tensile reinforcement cannot simply be interpreted as the splitting strength of the concrete cover.
- The new test method enables measuring the dowel's displacement and rotation.
- The observed behavior of the dowel mechanism in the tested members resembles that in shear cracks of reinforced concrete beams lacking shear reinforcement. However, it is crucial to validate the proposed expressions for the shear force carried by the tensile reinforcement in such beams.
- The models' comparison with the experimental results showed reasonably good agreement regarding the activation of the dowel action in the shear transfer mechanism from a new experimental method.

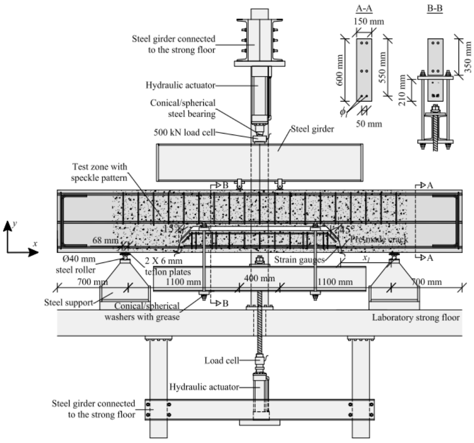

Figure 5. Test setup [32].

4. Factors effects on the shear strength of reinforced concrete beams

Many factors affect the shear strength of beam, including:

4.1 The Compressive Strength Effect

An important consideration that impacts the shear behaviour of RC beams lacking web reinforcement is the strength of the concrete, specifically its compressive strength, because of the brittle nature of concrete, the shear strength of High-Strength Reinforced Concrete (HSRC) beams does not increase proportionally to compressive resistance when compared to Normal-Strength Reinforced Concrete (NSRC) beams, according to experts in the field of structural engineering and concrete technology. Consequently, the current empirical equations in most building and bridge codes for estimating the shear capacity of HSRC beams are more conservative than those for NSRC beams. Conversely, shear failure in HSC beams with higher longitudinal steel quantities and shear span-to-depth ratios tends to be abrupt and brittle, lacking a clear indication prior to failure, similar to observations in the shear failure of HSC beams [33] and [34].

El-Din et al.,(2021) [35] investigated the shear behaviour of high-performance reinforced concrete beams involved symmetric loading with two equal concentrated loads. The beams were fully instrumented to measure applied loads, deflections, and strain in longitudinal steel bars. The results of the test included maximum loads, crack patterns, load-deflection behaviour, and strain in the reinforcement. The beams were reinforced with different configurations of shear reinforcement and longitudinal steel bars. The materials used in the experiment included high-performance concrete with silica fume, basalt aggregates, and superplasticizer. The experimental work aimed to understand the shear behaviour of high-performance concrete beams and included both experimental and numerical analysis. The results show that the use of web reinforcement in High-Performance Concrete (HPC) beams resulted in an improvement in cracking behaviour. This improvement was observed through better control of crack widths. The inclusion of web reinforcement helped to increase the stiffness of the beams and enhanced the post-peak load-deflection plateau. The use of web reinforcement also led to an increase in the ultimate load capacity of the beams. performance.

4.2 The effect of longitudinal reinforcement

The role of the longitudinal reinforcement ratio is crucial in preventing failure due to beam bending, particularly in beams without stirrups; thus, it is essential to consider the longitudinal reinforcement of the beam contribution in the shear strength. The shear strength is assumed to increase directly with the longitudinal reinforcement ratio. Consequently, beams with lower flexural reinforcement ratios exhibit lower diagonal cracking shear strength [36] and [37].

Karthick et al., (2015) [38] investigated the shear strength of the reinforced concrete beam without using shear reinforcement. Karthick et al. examined contribution of the longitudinal bars on the shear strength, by testing nine reinforced concrete beams to the failure, by acting two-point load on the beam. The researchers assumed variable constant except the steel ratio (ρ_w) and the shear span to the effective depth (a/d). The findings of this study; the increase in amount of the longitudinal reinforcement cause increasing in shear resistance also the stirrups accelerate the failure after the formation of the diagonal cracks and the initial shear cracks appears at distance (1.5 d to 2 d) from the face of the support. The effect of longitudinal reinforcement was obvious in the specimens without shear reinforcement, while the effect was is very low when in beams with stirrups.

Hamid et al., (2016) [39] investigated the effect of the amount of longitudinal reinforcement on the shear strength of Glass Fibre Reinforced Polymer (GFRP) reinforced concrete beams with steel stirrups. Also, they compared the numerical results with experimental results to provide a comprehensive analysis of shear strength design provisions and experimental program for GFRP RC beams. The finding showed acceptable agreement between the experimental and numerical results.

Christianto et al.**,** (2023) [40] studied the shear strength of High-Strength Concrete (HSC) and the influence of the longitudinal reinforcement ratio. The study compared and analyzed 12 reinforced HSC beams without coarse aggregate, using concrete mixes with compressive strengths ranging from 58 to 110 MPa. The specimens were tested until failure using a four-point bending test setup. The results showed that the existing formula for calculating shear strength overestimated the concrete shear strength, and a modified formula is proposed to improve accuracy for HSC shear strength. The suggested formula by Christianto et.al [40] showed a significant improvement in prediction of concrete shear strength, when it compared to other formulas used in this research.

$$V_c = \left[0.66\lambda s(\rho_w)^{1/3}\sqrt{f_c'}b_w d\right] \qquad (1)$$

$$V_c = \left[0.66\lambda_s(\rho_w)^{0.4}\sqrt{f'}\,{}_c b_w d\right] \qquad (2)$$

The researcher modified the ACI 318-19 [41] equation Eq. (1) to Eq.(2)

4.3 Effect of shear-span to depth ratio (a/d)

The distance (a) from the support to the primary concentrated load acting on the span is referred to as the shear span [42]. The ratio of a/d plays a crucial role in determining the beam's resistance. According to Fathifazl, et al.,[43], beams with an a/d ratio ranging from 1.5 to 2 behaved similar to a linked arch post inclined cracking, supporting the load through direct compression with struts connecting the loading plates to the supports, and the longitudinal tension reinforcement acting as a tie, resulting in high shear capacity. Conversely, beams with an a/d ratio between 2.7 to 4.0 did not exhibit the same shear resistance mechanism and failed shortly after the formation of the primary diagonal fracture. These observations align with the behaviour of typical concrete beams with similar a/d ratios. In general, the shear strength of reinforced concrete beams, with or without stirrups, experienced a significant decrease with an increase in a/d ratio [44].

Li et al., (2016) [45] presented an experimental investigation of the shear behavior of reinforced concrete beams reinforced with full-wrapping Fiber-Reinforced Polymer (FRP) strips when the shear span-to-effective depth ratio (a/d) is varied. The study offers a wide range of settings for observing and analyzing the behavior of these beams, with av/d ratios ranging from 1.0 to 3.5. The concrete's compressive strength, as determined by the cube test, ranges from 47 MPa to 55 MPa. Following a full-wrapping plan, the Carbon Fiber-Reinforced Polymer (CFRP) strips, each 60 mm wide, were individually adhered to the strengthened area. The strips were placed with a center-to-center spacing of 150 mm, as shown in Figure 6. Strain gauges were glued on the longitudinal and transverse steel reinforcements and the concrete surface. To accurately estimate the effective strains of CFRP strips, which determine their resistance to shear failure, we also installed strain gauges on each CFRP strip. This allowed us to accurately record the strain level at the point where the major shear cracks intersect, as well as the typical distribution of strain gauges. All specimens were tested in the four-point bending.

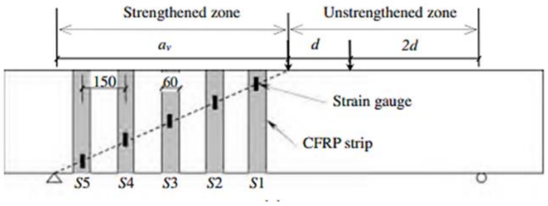

Figure 6. CFRP fixing places [45]

The results showed the contribution of the CFRP strips significantly enhanced shear capacity in the medium shear span-depth ratios (a/d); otherwise, the effect was lower in the large a/d and the least in the small a/d. The findings reveal the importance of the shear span/depth ratio (a/d) in the shear strength of reinforced concrete beams.

Alhamad et al., (2017) [46] investigated the shear behavior of deep beam with Basalt Fiber-Reinforced Polymer (BFRP) bars, which consisted of three beams with BFRP reinforcement bars and one beam with steel reinforcement as a reference. The testing was on different shear span-depth ratios (1.15, 1.48, and 1.82), all beams instrumented at the mid-span with strain gauges attached to the tension reinforcement. It was discovered that a diagonal crack propagated from the support to the closest loading point was the cause of all beam failures. Additionally, beams exhibited top concrete crushing in addition to the usual diagonal shear crack and were shown to have increased ductility close to failure. In comparison to their steel equivalents, the BFRP-RC beams often showed larger mid-span deflections and decreased stiffness. This is explained by the fact that BFRP bars, in contrast to steel bars, have a lower modulus of elasticity. Because big a/d ratio beams tend to act more like flexure-critical members than shear-critical ones, increasing the a/d ratio increased the mid-span deflection. Furthermore, the experimental results demonstrated a linear relationship between the shear capacity and the cubic root of the a/d ratio.

Hu and Wu, (2018) [47] investigated the effect of the shear span-to-depth ratio of reinforced concrete beams on the shear strength. By testing eleven reinforced concrete beams, they found that the concrete shear strength (Vc) can vary greatly from the shear force at first diagonal cracking (Vcr) to the fracture value; this difference changes as the shear span-to-depth ratio (a/d) varies. Also, they observed that not all stirrups yielded at the ultimate shear strength, they concluded that concrete shear strength (Vc) and stirrups strength (Vs) aren’t constant under increasing deformation

Al-bayati et al., (2019) [48] tested seven reinforced self-compacting concrete deep beams to study the behavior of deep beams with opening at varied shear span to depth ratio (a/d) strengthened by carbon fibers polymer strip (CFRP); the existence of the circular opening was in the shear span and the application of carbon fiber polymer (CFRP) strips was inclined. The flexural and shear reinforcement were identical throughout all specimens. The beams were subjected to two-point symmetric loads during testing. According to the experimental findings, the deep beam capacity was considerably decreased by 50% as a result of the web gaps within the shear spans as compared to the reference beam (without opening). The ultimate load for the reference beam and the strengthened beam was reduced by 21.7% and 22.5%, respectively, when the a/d ratio was increased from 0.8 to 1.2. Additionally, it was discovered that the externally inclined CFRP strips in deep beams enhanced the stiffness of deep beams with apertures and raised the ultimate strength by as much as 39.5%.

4.4 Effect of the beam size

The reduction in ultimate shear strength was observed with increasing beam depth, regardless of the maximum aggregate size and web reinforcement ratio, and that was more obvious in the beam without shear reinforcement [49]. The reduction was in the proportion of the experimental shear strength and the theoretical values; as a result, the beam size is considered a challenge for the researchers to better understand the shear strength of the reinforced concrete beams.

Kani, (1967) [50] conducted tests on four different beam series with varied depths. The effect of effective depth became very noticeable in the biggest beams, the proportion between the experimental shear strength and the shear equation values from codes is 40% lower than the smaller ones. The study proposed an equation of relative strength (r_u) rather than shear strength, as an indicator of failure. The equation incorporates three primary parameters ($\rho_w, a/d$ and the effective depth of the beam (d)) that influence the shear strength of the beam, as outlined below:

$$r_u = \left[0.215/\left(100\rho_w\sqrt{\frac{d}{25.4}}\right)\right]^{0.5} a/d \qquad (3)$$

Shioya et al**.,** (1990) [51] tested members with Varied depths. Throughout this examination, it was recognized the ultimate shear strength of the largest unit (3000 mm depth) was one-third in comparison with that in the smallest unit (100 mm depth). This implies that as the member depth increases, its capacity to withstand shear stress decreases. This phenomenon may be caused by a variety of factors, such as stress distribution within the member, material characteristics, or the method of applying loads. The discovery is significant because it emphasizes the influence of a structural member's size on its performance when subjected to shear stress. Such insights are critical for the design and evaluation of structures, helping engineers select appropriate member sizes to ensure both safety and effectiveness. Furthermore, it accentuates the necessity of comprehensive testing and analysis to grasp the material behavior under diverse loading conditions.

According to Shioya et al., [51] the shear strength of a reinforced concrete beam without shear reinforcement gradually decreases as the effective depth (d) of the beam increases and is generally called the size effect. The tests by Taylor**,** (1972) [52] revealed there is a reduction in size effect when the coarse aggregate size is adjusted proportionally to the beam size. Moreover, Taylor demonstrated that the decrease in strength in large beams with a normal (b_w/d) ratio, $(d/b_w < 4)$ is less severe. and this corresponding to the findings by Kani [50]. while, In the cases where $(\mathrm{d}/\mathrm{b_w} > 4)$,) Taylor has proposed that the design value of shear strength of concrete (Vc), should be reduced by 40%.

5. Various studies on the shear behavior of reinforced concrete beams

Dennison and Simon, (2014) [53] Presented an investigation the effect of incorporating metakaolin and steel fibres on the structural behaviour of reinforced concrete beams with rectangular cross-sections. Metakaolin was added in various percentages of (0%, 5%, 7.5%, 10%, and 12%) by weight of cement, while the steel fibres used ranged from 1.5% to 2.5% by weight of concrete. Four beams were subjected to shear testing, and it was observed that the shear strength of the samples containing metakaolin and crimped fibres was 32% higher than that of the reference beam. The most effective proportions of metakaolin and steel fibre were determined to be 10% and 1.5%, respectively.

Thórhallsson and Birgisson, (2014) [54] experimented the shear behavior of eighteen reinforced concrete beams without stirrups to assess the shear strength prediction. The investigation involved two variables: the height of beams was varied and the longitudinal reinforcement ratio of (1.55, 1.48, 1.41, 1.39, 1.35, and 1.31) %. The results were compared with the ACI Code, Model Code 2010, and Eurocode 2 (EC2). The results indicated that the three codes yielded different estimations of shear resistance. The shear design value calculated by EC2 and Model Code was lower than the value at which the initial shear fracture occurred. The ACI code consistently provides the most conservative estimate for shear resistance in all cases. The revised shear estimates from the Model Code yield 5% to 20% lower than the estimates obtained using EC2.

Azam et al., (2016) [55] examined the shear behaviour of reinforced concrete beams without shear reinforcement with corroded longitudinal steel reinforcement bars. Seven beams were tested. Three reference beams remained corrosion-free, while the other models were subjected to 3% and 10% corrosion. Three longitudinal reinforcement ratios were chosen; 0.91%, 1.21%, and 1.82%. After finishing the corrosion process, the models were tested under a one-point load. All beams failed to shear, but corrosion-prone beams failed to bond and had a lower bearing capacity than reference beams. The study found that beams with higher reinforcement ratios corroded at a slower rate than those with lower ratios. The longitudinal reinforcement's corrosion caused the beams to fail through bonding rather than shear failure. However, as corrosion levels increased, the load-bearing capabilities decreased. At 10% corrosion, the load-bearing capacity was 55% of uncorroded beam capacity.

Alsaraj et al., (2019) [55] presented an experiment on nine beams without stirrups using lightweight Modified Reactive Powder Concrete (MRPC) to study the shear behaviour. Multiple variables are used to demonstrate their effect on the diagonal cracking load and the maximum load: the Volume of Fraction (Vf), shear span to the effective depth (a/d), and the ratio of longitudinal reinforcement (ρ_w). Four different types of lightweight mixtures were tested. The factors in these mixes included the addition of 10% silica fume and the volume percent of steel fibre (Vf), with values of (0.0, 0.5, 1.0, and 2.0%) taken into consideration. After the testing of beams, it showed that by raising the volume fraction of fibers, the addition of steel fibers to the lightweight MRPC mixture increases the initial diagonal cracking load and ultimate load magnitude. In MRPC beams, increasing the longitudinal reinforcement ratio ρ from 3.29%, 4.26%, and 5.23% raised the ultimate load by 36.66% and 41.56% and the diagonal cracking load by 25.7% and 42.86%, respectively. In MRPC beams with Vf = 2.0%, increasing the shear span to effective depth ratio from 2.5-3.5 and 4 reduced the diagonal cracking load by 9.09% and 18.18%, respectively, and the ultimate load by 9.19% and 34.48 %, respectively. Also, the steel fibers volume fraction and the a/d ratio have an impact on the mode of failure.

Hasan and Saeed, (2023) [56] presented an experimental study to evaluate the shear strength and understanding the behavior of high strength concrete continuous beam without web reinforcement. They casted eight high strength beams with different length and tested them to the failure, they compared al sadeer et al. [57] equations and ACI318-14 aquations, two main variables were studied the compressive strength (fc ′) and shear span to the effective depth ratio (a/d) effect of the shear strength. The concrete's compressive strengths were measured at 63 MPa, 78.8 MPa, 85.9 MPa, and 92 MPa. The shear span to effective depth ratios were recorded at 2.41 and 3.33. There were two equal segments of continuous beams, and each section was examined under a one-point load. It was found that increasing compressive strength led to higher failure loads. However, the deflection had no significant effect. Increasing (a/d) resulted in lower failure load but higher defection. Also, both ACI 318-14[58] and the Sudheer et al. [57] equations seemed more conservative.

6. The prediction of shear strength

The shear strength of reinforced concrete beams represents the ultimate shear force that the beam can withstand before experiencing failure. This capacity is attained through a series of mechanisms that contribute the involvement of concrete, the ratio of longitudinal reinforcement ($\boldsymbol{\rho}_w$), shear reinforcement, shear span/effective depth ratio (a/d), compressive strength of concrete ($f'c$), concrete density, maximum size of coarse aggregate, beam dimensions, tensile strength of longitudinal and transverse reinforcement (f_y), clear length to depth ratio (L/d), the quantity of longitudinal reinforcement layers, and various factors that collectively impact the shear strength of the beam [59]. The design codes stated the shear equations based on the results of researchers. Also, the shear strength equations undergoing to continuous studies and conformation:

6.1. ACI318 prediction equation

The shear strength is based on an average shear stress on the full effective cross section (bwd). In a member without shear reinforcement, shear is assumed to be carried by the concrete web. In a member with shear reinforcement, a portion of the shear is assumed to be provided by concrete and the shear reinforcement, Eq.(2-4) [41].

$$\phi \mathrm{V_n} = \phi \mathrm{V_c} + \phi \mathrm{V_s} \tag{4}$$

The design shear strength ∅Vn must be larger than the factored shear force Vu at the section considered. and the reduction factor (∅) is 0.75 given by ACI 318-19 [41] for the design shear strength. The shear strength that provided by concrete (Vc) is assumed to be the same for the reinforced concrete beams with and without shear reinforcement and it is taken as the shear causing significant inclined cracking. This assumption is discussed in the ACI-ASCE Committee 426 reports[20].

According toACI318-19 [41], the shear strength of concrete (V_C) given as follow:
If $A_V \geq A_v\text{min}$
The less of;

$$\text{Vc}=\left[0.17\lambda\sqrt{f_c'}+\frac{\text{N}_\text{u}}{6\text{A}_\text{g}}\right]\text{b}_\text{w}\text{d} \qquad (5)$$

$$\text{Vc}=\left[0.66\lambda\left(\rho_\text{w}\right)^{1/3}\sqrt{f_c'}+\frac{\text{N}_\text{u}}{6\text{A}_\text{g}}\right]\text{b}_\text{w}\text{d} \qquad (6)$$

If $A_V \leq A_v\text{min}$, then:

$$\text{Vc} = \left[0.66\lambda_s\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_\text{g}}\right]b_w d \qquad (7)$$

For the shear reinforcement strength (V_S):

$$V_s = \frac{A_v f_{yv}(\sin\alpha+\cos\alpha)d}{s} \qquad (8)$$

Here, α represents the angle between the stirrups and the member's longitudinal axis, when stirrups are vertical α is zero so the equation will be:

$$V_s = \frac{A_s f_{yv} d}{S_v} \qquad (9)$$

6.2 British code (BS 8110)

The British code (BS 8110) [60] stated the equation for concrete shear strength calculation as follows:

$$V_c = \frac{0.79}{\gamma_m}\left(\frac{100A_s}{b_w d}\right)^{\frac{1}{3}}\left(\frac{400}{d}\right)^{\frac{1}{4}}\left(\frac{f_{cu}}{25}\right)^{\frac{1}{3}} \qquad (10)$$

γ_m: is the reduction safety factor

f_{cu}: Compressive strength of cube

6.3. Euro code (EN 1992)

Shear capacity without the shear reinforcement according to Euro code [61], calculated as follows:

$$V_{Rd,c} = \left[C_{Rd,c}k\left(100\rho_w f_{ck}\right)^{\frac{1}{3}} + k\sigma_{cp}\right]b_w d \qquad (11)$$

$$\text{k} = 1 + \sqrt{200/d} \leq 2.0, \rho_w \leq 0.02 \qquad (11a)$$

$$C_{Rd,c} = \frac{0.18}{\gamma_c} \qquad (11b)$$

The value of γ_c is a partial safety factor for concrete in the Eurocode. The typical value for γ_c is (1.5). However, this value can vary depending on specific conditions.

$$\sigma_{cp} = \frac{N_{Ed}}{A_c} \qquad (11c)$$

6.4. Canadian code

The equation of estimation the shear strength of the concrete in the Canadian code [62] didn't consider the a/d and the ratio of longitudinal reinforcement (ρ_w),it is given as follows:

$$V_C = 0.2(fc')^{0.5}b_w d \qquad (12)$$

6.5 Investigations on Shear Strength prediction: conferment and development

Experimental and statistical studies focus on verifying the accuracy of existing shear strength models and codes, such as those provided by American Concrete Institution (ACI) code, Eurocode (EC2), and Canadian Standards Association (CSA). These studies often highlight the conservativeness or shortcomings of current models and provide empirical data to support or refute them. Some of this study will be mention in this section:

Zsutty, (1968) [63] suggested new formula to calculate the cracking shear strength of beams, when a/d >2.5, based on empirical results and statical regression analysis using the following expression.

$$V_c = 2.3\left(fc'\rho_w\frac{d}{a}\right)^{1/3}b_w d \qquad (13)$$

Ghadhban**,** (2005) [64] presented a study on predicting the shear strength of reinforced concrete beams, by gathering the experimental results of 689 reinforced concrete beams that failed in shear. The study examined the impact of several essential factors on the shear prediction: the shear span-depth ratio (a/d), the compressive strength of the concrete, the width of the beam, the beam depth, the longitudinal reinforcement ratio, and the vertical web stress were all examined. Regression analysis was employed. The researcher proposed the following equation for beams without shear reinforcement:

$$\emptyset V_c = \emptyset 65(f'\mathrm{c})^{0.37}(\rho s)^{0.44}(\mathrm{a/d})^{0.79}(bwd)^{0.77} \quad (14)$$

$$\emptyset = 0.48$$

Arslan**,** (2008) [65] presented a study of proposed alternating shear strength equations for the reinforced concrete beams without shear reinforcement (slender beams). The collected data were over 80 sources of reinforced concrete beams tests covering broad range of variables of the beams properties and the method of testing, the proposed equations for the cracking shear strength have been used for the existing data for the Normal Concrete Strength (NSC) also concrete with High Strength (HSC) for slender beams and the results were compared with the equations for the cracking shear based on ACI 318.The cracking shear strength capacity of thin beams without stirrups can be satisfactorily predicted using the suggested shear strength equations. Nevertheless, more investigation is needed to validate the suggested equations because there is a lack of test data for high-strength concrete parts also, increasing ρ, ($f'c$), and a/d does not considerably affect the ratio of experimental to suggested cracking shear strength, however the shear test results are not uniform when it comes to slender beams, the suggested equation is:

$$V_c \;=\; 0.15(f'\mathrm{c})^{0.5} + 0.02\,(f'\mathrm{c})^{0.65} * bwd \qquad (15)$$

Kuchma et al. (2019) [66] reviewed the shear design relationships in ACI 318-14[58] for the concrete Shear Strength (Vc) that previous researchers suggested, highlighting the complexity of shear resistance in beams and the relevance of various design parameters. They presented a modified formula in ACI 318-19 [41] based on outcomes of a long-term effort within the ACI community to advance one-way shear design provisions. The researchers introduced a general relationship for calculating Vc in reinforced concrete members without shear reinforcement (non-prestressed members (that considers the effects of member depth, the ratio of longitudinal reinforcement, and the effect of axial stress. The new relationship is:

$$V_c = \left(0.66\lambda_s\lambda(\rho_w)^{\frac{1}{3}}\sqrt{f_c'} + N_u\left(6A_g\right)\right)b_w d \qquad (16)$$

Where λs is the size effect factor and it is equal to $\sqrt{2/(1+0.004d)} \leq 1$.

They found that using a minimum shear reinforcement showed no significant effect of size on shear strength, and the basic formula can be used to predict shear strength.

$$V_c = \left(0.17\lambda\sqrt{f_c'}\right)b_w d \qquad (17)$$

Rizqyani & Tavio, (2022) [67] conducted a statistical investigation by comparing the results of the predicted shear strength obtained by five available formula codes (the Indonesian code SNI 2847-2019, the ACI code 318-19, the Euro code EN 1992, New Zealand standard NZS 3101.2 and Canadian standard CSA A23.3) with the experimental results of 129 tested concrete beams. The comparison was to determine the closest predictive strength formula to the experimental test results. The details of the chosen beams were taken from various research data. There was a variety of variables in this study. The study found that SNI regulations used in this instigation were unsafe for ρ_w < 1% and overestimated shear strength for beams with effective depth (d) > 500 mm. The Canadian Standard is the most conservative for ρ_w < 1%, while the New

Zealand Standard and Euro code are reasonably accurate results, with $V_{Exp.}/V_{code}$ averages of 1.16 and 1.43, respectively. For normal-strength concrete, Canadian is the most conservative (average ratio of $V_{Exp.}/V_{code}$ 1.87). All approaches exhibited similar behavior when the beam is very deep. A reduction in shear strength is observed, corresponding to the depth increase when the beam has an effective depth of d > 500 mm. The researchers modified the ACI formula of shear strength, which is already mentioned before Eq. (6); they changed the term of compressive strength to as follows:

$$V_c = \left[0.66\lambda(\rho_w)^{1/3} f_c'^{\,0.53} + \frac{N_u}{6A_g}\right] b_w d \qquad (18)$$

7. Conclusion

Shear failure in reinforced concrete beams remains a critical concern due to its sudden and catastrophic nature. This study aims to gain a deeper understanding of the shear behavior of reinforced concrete beams, especially without shear reinforcement and highlights the findings from previous studies. Despite significant research, accurately predicting shear strength is challenging because of the complex interplay of various factors.

One of the big challenges for the researchers is understanding the shear failure mechanisms and failure modes of RC beams. Based on the researcher's findings, the shear mechanisms are essential for effective design, as their interaction complicates shear strength prediction. These mechanisms have complex interactions that have a significant impact on shear strength. Various factors impact the shear strength of a structure, such as the compressive strength of the concrete, the ratio of longitudinal reinforcement, the shear span-to-depth ratio, and the size of the beam. These factors have been extensively studied and are considered in design codes. The Existing design codes often provide conservative estimates for shear strength, particularly for high-strength concrete and large-sized beams. This conservatism can lead to overdesign and increased costs. Current codes may not adequately assess the shear behavior of high-performance concrete and deep beams, necessitating further research and refinement.

Further Comprehensive experimental studies are needed to investigate the effects the loading rate and the dynamic loads effect on the shear behavior. Also, more studies on high-performance concrete and its shear behavior under different loading conditions are necessary. Advanced numerical modeling can complement experimental studies, providing insights into complex shear mechanisms and predicting behavior under various scenarios. Validating these models with experimental data will enhance their reliability and practical applicability and using the advanced method of testing and observation such us digital image correlation (DIC) for more accurate results. Shear reinforcement design is crucial to enhance the ductility and reliability of reinforced concrete beams. Optimizing reinforcement layouts will improve shear capacity and crack control

Abbreviations

A_g	Total section area of concrete beam
A_s	Cross section area of bars
A_v	Cross section area stirrup
b_w	Width of the beam web
d	Effective depth of the beam
a	Distance from the load point to support
a/d	Shear span/effective depth
V_c	Shear strength provided by concrete
V_s	Shear strength provided by stirrups
f_c'	Compressive strength (cylinder)
f_{cu}	Compressive strength (cube)
f_{yv}	Yield stress of stirrup
S_v	Spacing between stirrups

$\rho_w, \rho s$	Longitudinal reinforcement ratio
N_u	Axial force
N_{Ed}	Design axial force in Eurocode
σ_{cp}	Compressive stress due to axial force
λ	Lightweight concrete modification factor
λ_s	Size effect factor
γ_m	Reduction factor in British standards
γ_c	Reduction factor in Eurocode
$\emptyset$	Reduction factor in ACI

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