

COMPARATIVE STUDY OF SHEAR-SPAN-TO-DEPTH AND REINFORCEMENT RATIO ON HIGH-STRENGTH CONCRETE BEAMS

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Abstract

The shear strength of reinforced concrete members with or without shear reinforcement is influenced by the shear span to effective depth and longitudinal tensile reinforcement ratios. In high-strength concrete, if the paste has a higher strength than the aggregates, then propagation of cracks is possible through the aggregates rather than around the aggregates, and the concrete may fail with a brittle failure, which is against most of the guideline's philosophies. This paper investigates experimentally the influence of the shear-span to effective depth ratio and the longitudinal tensile reinforcement ratios on the behavior of the shear strength of HSC beams having no shear reinforcement. A total of fifteen reinforced high-strength concrete beams with different longitudinal reinforcement ratios were fabricated and then tested under a two-point bending test with shear-span to effective depth ratios varying from 1 to 3. Experimental results were compared based on design codes and state-of-the-art models. The influence of shear-span to effective depth ratio and longitudinal tensile reinforcement ratio is unaccounted for in most design guidelines and prediction models; therefore, the predicted values are either underestimated (up to 50%) or overestimated, except for the Zsutty Model, which has accurately predicted the shear strength values for all shear-span to effective depth and longitudinal tensile reinforcement ratios. As in the future, high-strength concrete will be more likely used in RC construction, this study directs the understanding of model assumptions for shear prediction before its use.

Keywords:

Shear Strength,
 High-Strength Concrete,
 Longitudinal Reinforcement Ratio

1 Introduction

In concrete structures, shear strength persists, an issue of great significance. The main objective of designing the RC members for shear is to prevent shear failure. Both the concrete and web reinforcement contribute to the shear strength of reinforced concrete members. According to ACI 363R 2010, concrete mix has a compressive strength f'_c at 28 days greater than 41.36 MPa or 6000 psi is classified as high-strength concrete (HSC) [1]. In most construction works; HSC is preferred over normal-strength concrete (NSC) due to its enhanced mechanical and durability properties. In HSC, if the paste has a higher strength than aggregates, then propagation of cracks is possible through the aggregates rather than around the aggregates [2]. Smooth cracks are formed through the aggregates, which results in a reduction of aggregate interlock, which may lead to a brittle failure [3]. This study explores how aggregate characteristics influence

crack propagation and interlock mechanisms, providing insights into how smooth cracks can affect overall material performance and lead to brittleness. HSC possesses improved strength and is generally used in bridge girders, heavily loaded columns, and precast elements. It reduces the member size and ultimately the overall cost.

The shear resistance of reinforced concrete structures is a complex problem, and extensive numerical and experimental research studies have been carried out by various researchers over the last few decades to consider different parameters in shear prediction models [4-6]. These parameters are concrete compressive strength, tensile reinforcement ratio, dowel action, aggregate interlocking, bond stress between concrete and steel, crack spacing, and the ratio of shear span to effective depth. These factors influence the mechanism of shear failure in RC Beams. Table 1 summarizes some of the important parameters considered in universally used shear design models and guidelines. Ratios of shear span to effective depth and longitudinal tensile reinforcement are the considerable parameters that influence the shear resistance [7]. The ratio of shear span to effective depth considers the ratio between bending moment (M) and shear force (V) in the same cross-section and can be numerically calculated as a/d , where a is the distance from the supports to the point of application of force and d is the effective depth of the cross-section [8].

In NSC beams, the early theories for the mechanism of shear transfer are analytically based on various design codes like EC 2-1992 [9] and ACI 318-2014 [10], while some others are based on the field theory of modified compression, like CSA23.3-2004 and some are based on crack theory for critical shear, such as Fib Model Code 2010 [11, 12]. The empirical theories are formed by truss and variable truss analogies and beam-arch actions that do not consider the bond action between aggregate interlock and reinforcement [13, 14]. The modified compression field theory considers the aggregate interlock, the compression zone, longitudinal reinforcement, the aggregate interlock, and the transfer of shear across cracks [15].

Based on a/d ratio, the RC beams are categorized into three groups: normal beams with a/d ratio greater than 2.5, short beams with a/d between 2.5 and 1, and deep beams with a/d ratio between 1 and 0 [16]. It is also known that, as compared to slender beams, the ultimate shear strength V_{ult} in deeper members is progressively larger. In the last five decades, theoretical and experimental studies have been performed to evaluate the influence of a/d on the shear strength of RC beams. Clark observed that the shear strength of RC members is a function of a/d , longitudinal reinforcement ratio, and concrete compressive strength [17]. Leonhardt and Walther studied the effect of size in RC members subjected to shear with a/d ratios ranging from 3 to 8. Their research also investigated the influence of the number of longitudinal reinforcement bars and the dimensions of the beams [18]. Kani investigated the size effect on the shear resistance of RC beams without stirrups and having a/d ratio ranging from 1 to 8 [19]. Test results have shown a significant influence of a/d on the shear resistance.

Table 1: Parameters considered for Shear prediction in different models

Parameters	ACI 318-14	Eurocode	CSA	Kuo et al.	Zsutty	Bazant et al.
Aggregate size	x	x				
Compressive Strength	x	x		x	x	x
a/d				x	x	x
ρ	x	x	x	x	x	x
Size effect based on depth	x		x			

Several experimental studies have concluded that the shear behavior of RC beams without and with web reinforcement is significantly influenced by the a/d ratio and concrete compressive strength [20, 21]. An inclined crack is formed for a value of a/d less than 1.0, which joins the support and point of load and eliminates the horizontal shear flow from the concrete compression zone to the longitudinal reinforcement, and the behavior is changed to arch action from beam action. For a/d values from 1.0 to 2.5, redistribution of the internal forces takes place, an inclined crack is formed, and arching action dominates the beam

behavior. For a/d ratios between 2.5 and 5.0, the beam action dominates the beam behavior before it ultimately fails in flexure [22].

Fib Model Code 2010 was established to demonstrate the significance of aggregate interlock on the shear strength of RC members [11]. Concrete is defined as a composite material of two-phase, rigid sphere aggregates and cement paste, which surrounds the rigid sphere aggregates. The cracks in concrete were modeled to propagate only around aggregates, and the contact area of the crack depended upon crack kinematics, the size of the aggregate, and the ratio of the volume of coarse aggregate to that of total aggregate.

Chen et al. have investigated that the shear resistance capacity of HSC beams does not vary in the same proportion to concrete compressive strength [23]. HSC beams without shear reinforcement were tested for exploration of overall shear behavior. The shear strength variation of HSC beams is correlated to the roughness of the fracture surface. The roughness index decreases with an increase in concrete compressive strength, indicating that failure surfaces in HSC beams are smoother than those in NSC. Shear strength of HSC beams with no shear reinforcement and compressive strength close to 70 MPa are investigated by considering various a/d ratios [24]. The results obtained are compared with various design codes and shear prediction models, such as the Canadian Standard, ACI 318, Zsutty Equation, Bazant Equation, and CEP-FIP Model. Zsutty's model was found to best correlate to the testing results, and a simplified equation is presented for the prediction of the shear strength of HSC beams.

Hu et al. have experimentally evaluated shear crack width and shear strains in RC beams using digital image correlation. The crack width is correlated to shear strength and deflection [25]. The results of image correlations are compared with various formulas provided by ACI and AASHTO for the prediction of the first diagonal crack shear V_{cr} and the total shear capacity V_c . The consequence of the shear-span-to-depth ratio on V_c and V_s is experimentally studied [26, 27]. The results showed that with a small variance in the a/d ratio, V_c has large values compared to V_{cr} . Furthermore, it was found that for higher a/d ratios, the design codes provide unconservative values.

The influence of variation in the a/d ratio on the shear resistance capacity (V_c) provided by concrete is investigated by an experimental approach [28]. A model is developed by considering variations in the a/d . Both V_c and V_s were found to be significantly influenced by a/d .

This comparative study aims to evaluate the influence of a/d and longitudinal reinforcement ratios on the shear behavior of HSC beams having no shear reinforcement. A comparison is made between different design codes and state-of-the-art models. The experimental program consisted of beams with different a/d and tensile reinforcement ratios. As in the future, HSC will be more likely used in RC construction, this study directs attention to the need for extensive research to understand the shear mechanism in HSC beams.

2 Experimental Work

2.1 Materials Properties

The materials utilized in this study consisted of coarse and fine aggregates sourced from magnetite quarries in Kabal Swat, Pakistan. The aggregates, derived from magnetite rock, were selected for their durability and strength, with a maximum size of 22 mm. Proper blending and grading were performed to achieve optimal packing, which is crucial for the performance of high-strength concrete (HSC) as noted in previous studies [30].

To ensure adequate workability and performance, we incorporated Ultra Superplast 470, a high-range water-reducing admixture (HRWRA), and Ultra AEA 192, an air-entrainer admixture (AEA), into the concrete mix. The mix design was conducted according to the ACI method (ACI 211.1) [29], with all measurements taken by weight.

Concrete cylinders (150 mm diameter and 300 mm height) were prepared from each batch to determine compressive strength at the time of beam testing. After curing in a water tank for 28 days, the average compressive strength of the concrete cylinders was found to be 60.18 MPa, which aligns with findings from similar studies that emphasize the importance of compressive strength in shear capacity assessments [30]. The concrete mix design details and properties are summarized in Table 2.

Uniaxial tension tests were performed on three samples of longitudinal tensile reinforcement, made from bars with diameters of 12 mm and 14 mm. The average yield and ultimate strengths of the reinforcement were determined to be 420 MPa and 520 MPa, respectively, with an elastic modulus of 210

GPa. These values are consistent with the mechanical properties reported in the literature for conventional steel reinforcement [32,33]

Table 2: Mix Design Details and properties of Concrete.

w/c	Unit Weight (kg/m ³)						Slump (mm)	F_c' (MPa)
	Cementitious materials	Fine Aggregate	Coarse Aggregate	water	HRWRA	AEA		
0.33	539.34	533.42	1094.70	177.98	2.52	0.14	81.23	60.18

2.2 Specimen Designs

To investigate the influence of shear-span-to-effective-depth ratios (a/d) and longitudinal reinforcement ratios on the shear behavior of HSC beams, we designed and constructed 15 beam specimens in accordance with the provisions of ACI 318-2014 [10]. The beams were constructed to represent five different a/d ratios and three different longitudinal reinforcement ratios. The cross-sectional details of the HSC beams are illustrated in Figure 1.

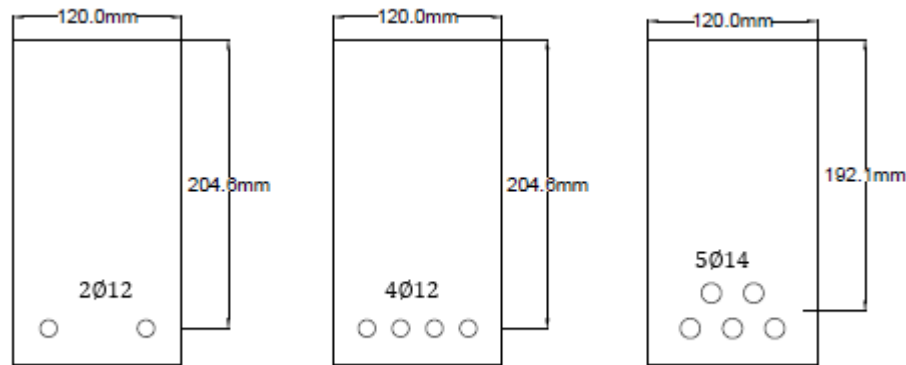


Fig 1: Cross Sectional Details of *HSC* Beams without shear reinforcement

(a): $\rho = 0.92$ (b): $\rho = 1.84$ (c): $\rho = 3.13$

A two-point bending test was conducted, with the load applied in a displacement-controlled manner at a constant rate of 0.4 mm/min until all beams failed in shear. Each beam had a length of 1350 mm and was simply supported. The supports were adjusted according to the specified a/d ratios, as summarized in Table 3. Notably, to evaluate the effect of a/d and longitudinal reinforcement ratios on shear strength and failure behavior, no stirrups were used in the design of the beams. This approach is consistent with findings from previous research indicating that shear strength in HSC beams can be significantly influenced by these parameters [31]

Table 3: Details of *HSC* Beams

Beams	b (mm)	d (mm)	a/d	Ref ratio
B1	120	204.6	1	0.92
B2	120	204.6	1	1.84
B3	120	204.6	1	3.13
B4	120	204.6	1.5	0.92
B5	120	204.6	1.5	1.84
B6	120	204.6	1.5	3.13
B7	120	204.6	2	0.92
B8	120	204.6	2	1.84
B9	120	204.6	2	3.13

B10	120	204.6	2.5	0.92
B11	120	204.6	2.5	1.84
B12	120	204.6	2.5	3.13
B13	120	204.6	3	0.92
B14	120	204.6	3	1.84
B15	120	204.6	3	3.13

2.3 Test Setup

The experimental setup utilized a Universal Testing Machine with a capacity of 40 tons to apply load gradually to the HSC beams until shear failure occurred. A two-point loading configuration was employed, utilizing a rigid steel spread beam to distribute the load evenly. To prevent local concrete crushing, a thick neoprene pad (150 mm by 30 mm) was placed under the loading point. The beams were simply supported, and the complete setup is depicted in Figure 2.

During testing, the loads were applied until shear failure was recorded. The loads corresponding to the failure of each beam were meticulously documented and analyzed. The peak load that caused the shear failure was recorded, and half of this value was taken as the experimental shear strength of the beam. The experimentally calculated shear strength values for all beams are summarized in Table 3.



Fig. 2: Testing Setup of HSC Beam

2.4 Design Codes and Models for Shear Strength Predictions

The shear strength of concrete members depends on numerous parameters, and various studies have been carried out to discover the actual behavior of shear failure. The various parameters are the compressive strength of concrete, longitudinal tensile reinforcement ratio, ratio of shear span to effective depth, type, and size of Aggregate, loading type, support conditions, etc. For design purposes, the shear capacity of concrete members is calculated through the available equations in various designing codes and models based on different concrete grades and shear transfer mechanisms. The following is a detailed description of these equations.

2.4.1 ACI Equation (318-14)

For concrete members having no transverse shear reinforcement the ACI code 318-14 predicts shear strength by the following two equations:

For $a/d \geq 2.5$

$$V_c = \left(0.16\sqrt{f'_c} + 17\rho \frac{V_u d}{M_u} \right) b_w d \quad (1)$$

For $a/d \leq 2.5$

$$V_c = \left(3.5 - \frac{2.5M_u}{V_u}d\right) \left(0.16\sqrt{f'_c} + 17\rho \frac{V_u d}{M_u}\right) b_w d \quad (2)$$

Where:

- f'_c - 28 days compressive strength of concrete in MPa, and is limited to 69 MPa
- ρ - longitudinal reinforcement ratio,
- b_w - width of the beam in mm,
- d - effective depth in mm,
- M_u - ultimate moment in Nmm,
- V_u - ultimate shear force in N,
- a/d - shear-span to effective depth ratio,

ACI Code does not consider the longitudinal tensile reinforcement ratio and gives importance to M_u and V_u parameters.

2.4.2 Eurocode 2 (EN 1992-1-1)

According to Eurocode 2 Standards, the equation for the prediction of the shear strength of concrete members without shear reinforcement is given by

$$V_c = \left[\frac{0.18}{\lambda_c} k (100\rho f_{ck})^{\frac{1}{3}} + 0.15\sigma_{cp} \right] b_w d \quad (3)$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2 \quad (4)$$

Where:

λ_c - a factor for lightweight concrete,

σ_{cp} - the axial stress in member.

The Eurocode 2 considers the axial stress in the member, effective depth, and longitudinal tensile reinforcement ratio but neglects the effect of the shear span.

2.4.3 Australian code AS 3600-2018

According to Australian code Standards, the equation for the prediction of the shear strength of concrete members without shear reinforcement and having no axial stress is given by

$$V_c = k_v b_w d_v \sqrt{f'_c} \quad (5)$$

$$k_v = \left[\frac{200}{1000 + 1.3d_v} \right] \quad (6)$$

Where d_v is the shear depth and can be considered as 0.9d or 0.72h.

2.4.4 New Zealand code, NZS 3101

The New Zealand design code for shear strength prediction of RC beam is applicable for f'_c up to 100 MPa. The ultimate contribution of the concrete component V_c is given by

$$V_c = (0.07 + 10\rho)\sqrt{f'_c}b_w d \quad (7)$$

2.4.5 Canadian Code CSA A23.3-04

The Canadian design code for shear strength prediction of RC beams applies to concrete members with compressive strength less than 80 MPa. According to Canadian code standards, the equation for shear strength prediction of concrete members having no shear reinforcement and having a maximum size of coarse aggregate not less than 20 mm is given below

$$V_c = (\lambda\beta\sqrt{f'_c}b_w d_v) \quad (8)$$

$$\beta = \frac{230}{1000+d_v} \quad (9)$$

2.4.6 Chinese code GB50010-2010

In Chinese code contribution of concrete to the shear strength of the beam is given by

$$V_c = 0.025\beta_c f'_c b_w h_o \quad (10)$$

Where β_c is coefficient of concrete influence and h_o is effective depth of the cross-section.

2.4.7 Bazant and Kim Model

Bazant and Kim have evaluated the following equation for prediction of shear strength contributed by concrete

$$V_c = \frac{10^3 \sqrt{f'_c}}{\sqrt{1 + \frac{d}{25d_a}}} \left(0.083 \sqrt{f'_c + 20.69 \sqrt{\frac{\rho}{\left(\frac{a}{d}\right)^5}}} \right) \quad (11)$$

The Equation presented by Bazant and Kim for prediction of shear resistance capacity of concrete members looks complex, but it considers all the factors which influence the prediction of the shear resistance capacity of concrete members.

2.4.8 Zsutty Model

Zsutty has evaluated the following equation for prediction of shear strength contributed by concrete

$$V_c = 2.17 \left(f'_c \rho_t \frac{d}{a} \right)^{\frac{1}{3}} b_w d \quad a/d \geq 2.5 \quad (12)$$

$$V_c = 2.17 \left(2.5 \frac{d}{a} \right) \left(f'_c \rho_t \frac{d}{a} \right)^{\frac{1}{3}} b_w d \quad a/d < 2.5 \quad (13)$$

The equation stated by Zsutty for prediction of shear resistance capacity of concrete members is very simple and appropriate to predict shear resistance capacity of both long and shorter beams as it considers the size affect and the longitudinal reinforcement ratio.

2.4.9 Kuo et al. Model

Kuo et al. after performing several experimental tests have formulated an equation for prediction of the shear strength of concrete beams with no shear reinforcement which is given below

$$V_c = 1.17 \left(\frac{a}{d} \right)^{-0.7} \sqrt{f'_c} b_w c \leq 0.83 \sqrt{f'_c} b_w c \quad (14)$$

$$c = \sqrt{2\rho + (\rho n)^2} - \rho n \quad (15)$$

Where n is the ratio of modulus of elasticity of steel to that of concrete.

The equation formulated by Kuo et al. for the prediction of the shear strength of concrete members gives reliable results as it includes shear-span-to-depth, longitudinal tensile reinforcement ratios, and the ratio of modulus of elasticity of steel to that of concrete.

2.4.10 Model Code 2010 Provisions

The fib Model Code 2010 provides a comprehensive framework for predicting the shear strength of concrete beams, incorporating advanced physical-mechanical models based on observed behavior at the mesoscale level. The provisions for shear design apply to both members with and without shear reinforcement and represent a significant advancement over previous empirical methods.

The shear strength V_c of concrete beams is determined using the following equation:

$$V_c = k \cdot \sqrt{f'_c} \cdot b_w \cdot d \quad (16)$$

Where

- K is a coefficient that accounts for the effects of various parameters including the size of the member and the presence of shear reinforcement.
- f_c' is the compressive strength of concrete.
- b_w is the width of the beam.
- d is the effective depth of the beam.

This equation emphasizes the importance of considering both geometrical and material properties in shear strength predictions. The inclusion of the coefficient k allows for adjustments based on member size and loading conditions, ensuring that design practices remain robust across different scales.

3 Results and Discussion

The experimentally measured values of shear resistance capacity for the beams having no shear reinforcement are compared to the predicted values inferred from design codes and shear prediction model equations proposed by several authors. From Fig. 3, it can be observed that *HSC* beams with no longitudinal reinforcement have a similar crack pattern as that of *NSC* beams. Comparison of experimental results with predicted results reveals that the a/d ratio significantly affects the shear-resisting capacity of concrete members. Most equations from design codes and shear prediction models underestimate the shear resisting capacity, while some overestimate it.



Fig. 3: Shear Crack pattern in *HSC*

Table 3 illustrates experimental values of shear strength for HSC beams under a two-point loading test. It can be observed that with an increase in the longitudinal tensile reinforcement ratio, the shear resistance capacity of HSC beams with no shear reinforcement also increases. This is because when the diameter of longitudinal reinforcement increases, the dowel action becomes more prevalent to resist the shear. The experimental results also show that with an increase in the a/d ratio from 1 to 3, the shear capacity of HSC beams having no shear reinforcement decreases, i.e., for 3.13% of steel, it is 156.3 KN, 87.53 KN, 73.54 KN, 53.48 KN, and 49.13 KN.

Table 3: Experimental results of Shear Strength

Beam ID	V_c Failure (KN)	Beam ID	V_c Failure (KN)
B1	99.654	B9	73.547
B2	124.785	B10	36.542
B3	156.371	B11	43.789
B4	57.862	B12	53.489
B5	72.348	B13	30.987
B6	87.534	B14	39.564

B7	45.398	B15	49.135
B8	55.478		

Figs. 4 to 8 demonstrate the comparison of various equations of the design codes and shear prediction models to the experimental results. The ACI code considers both a/d and longitudinal reinforcement factors; however, it underestimates the shear capacity of *HSC* beams having no shear reinforcement; the difference is less for higher a/d ratios. The Canadian, Chinese, and Australian codes depend on the compressive strength of concrete and do not include the a/d and longitudinal reinforcement ratio factors; therefore, they have constant and nearby equal values of 38. KN, 36 KN, and 27.66 KN, respectively. The Indian code has the lowest value among all codes. The New Zealand code considers the longitudinal reinforcement ratio factor and underestimates the shear prediction results for a/d less than 1.5 and gives nearly equal values to experimental values for a/d greater than 1.5. The Eurocode 2 underestimates a/d ratios less than 1 and overestimates a/d ratios greater than 1.

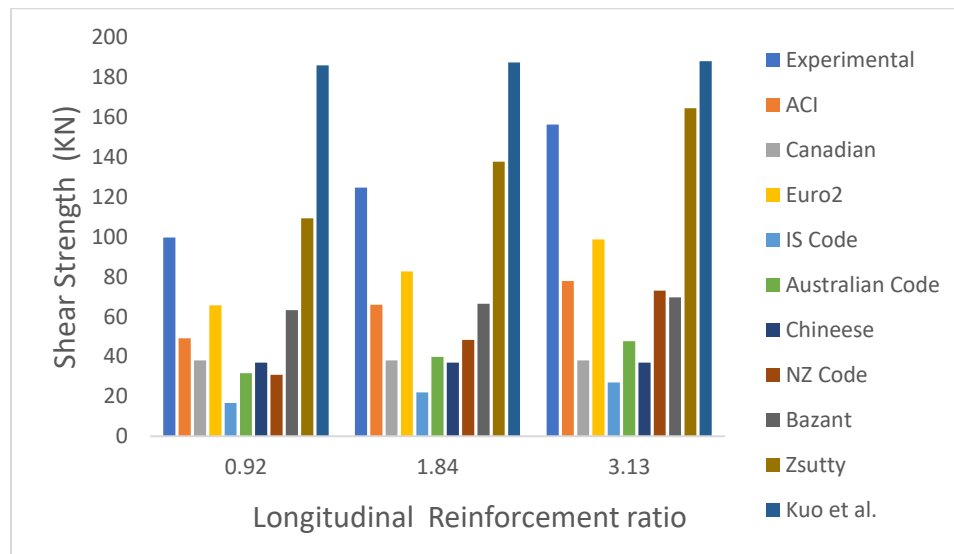
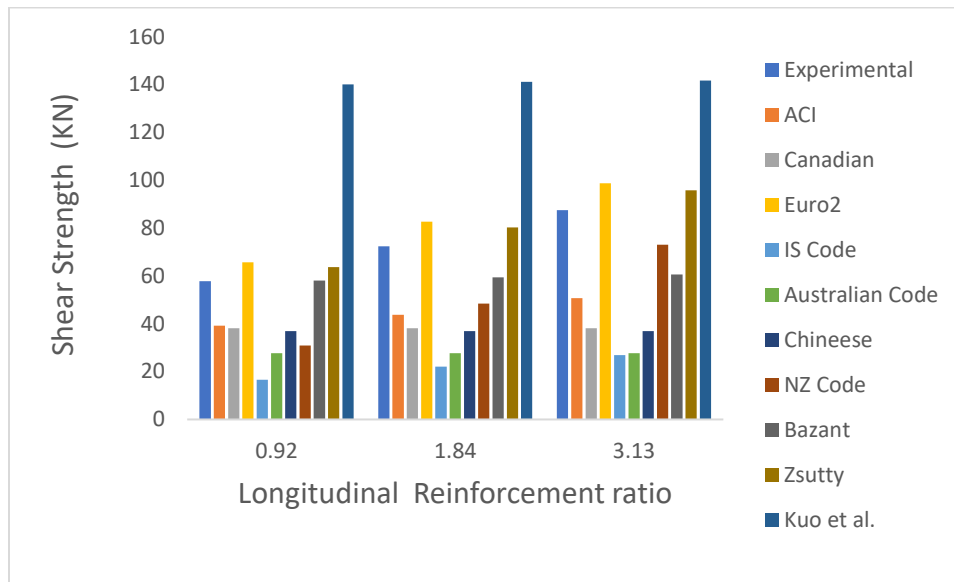
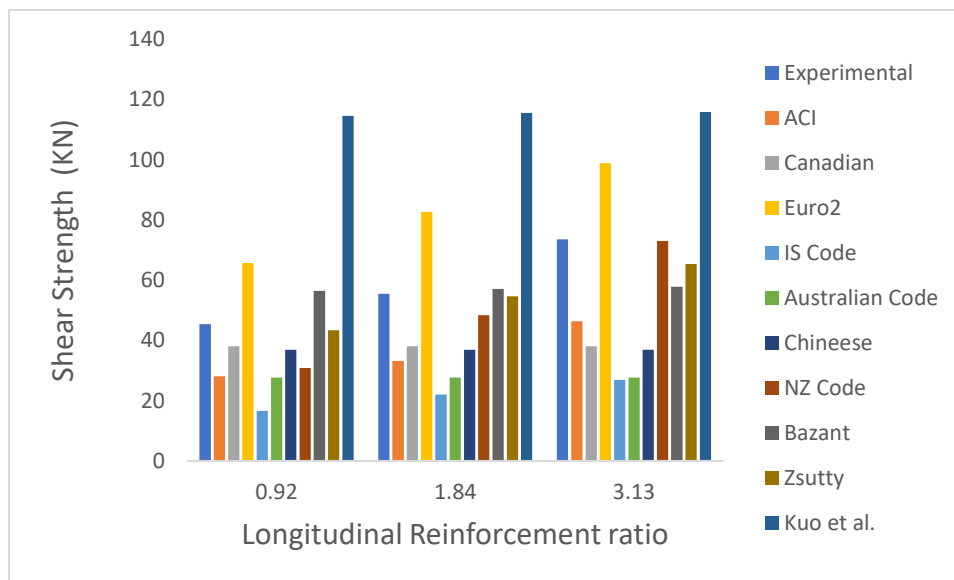


Fig. 4: Shear Strength vs longitudinal reinforcement ratio for $a/d=1$

Fig. 5: Shear Strength vs longitudinal reinforcement ratio for $a/d=1.5$ Fig. 6: Shear Strength vs longitudinal reinforcement ratio for $a/d=2$

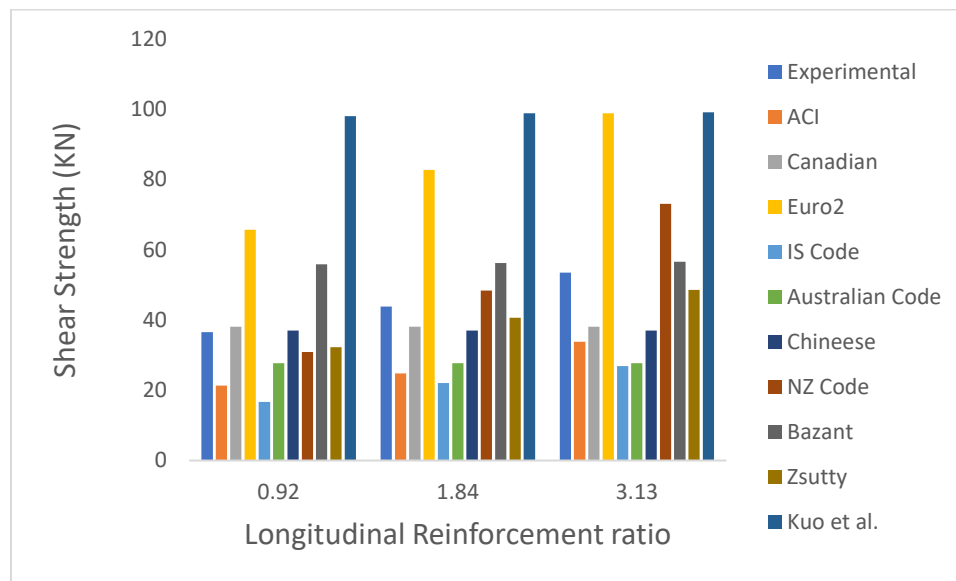


Fig. 7: Shear Strength vs longitudinal reinforcement ratio for $a/d=2.5$

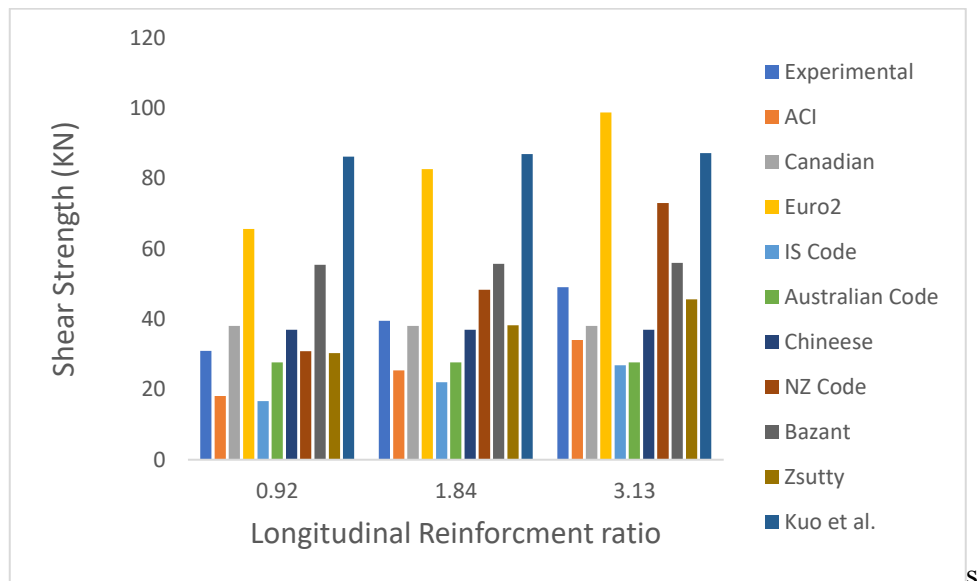


Fig. 8: Shear Strength vs longitudinal reinforcement ratio for $a/d=3$

The Bazant and Kim model results in lower values of shear strength for an a/d ratio less than 1.5 and higher values for an a/d ratio greater than 1.5. The Bazant and Kim model considers all parameters required for the calculation of the shear capacity of concrete members, i.e., longitudinal tensile reinforcement ratio, concrete compressive strength, the ratio of shear span to effective depth, and the side effect of the member, but it still underestimates or overestimates the shear capacity of the *HSC* beams. The Zsutty prediction model for shear closely predicts the shear capacity of *HSC* beams with no shear reinforcement. Compared to other code models, the Results of the Zsutty shear prediction model are very close to experimental results. The shear resistance capacity calculated from Kuo et al.'s model equation

indicates higher values of shear than the experimental shear strength since it includes the parameter n , the ratio of the elastic modulus of steel to that of concrete.

The experimental investigation tested fifteen reinforced high-strength concrete (HSC) beams with varying longitudinal reinforcement ratios and shear-span to effective depth ratios (a/d) ranging from 1 to 3. The results demonstrated a strong dependence of shear strength on both the a/d ratio and the longitudinal tensile reinforcement ratio (ρ). Specifically, beams with lower a/d ratios exhibited higher shear strength, consistent with the Model Code 2010 (MC2010) predictions, while higher a/d ratios led to decreased shear capacity and earlier shear cracking. The longitudinal tensile reinforcement ratio (ρ) significantly influenced shear strength, with higher reinforcement ratios improving shear resistance, thereby validating the MC2010's assertion that increased tensile reinforcement enhances shear capacity. Comparisons with various design codes revealed that most models underestimated or overestimated shear strength by up to 50%, with the Zsutty Model providing the most accurate predictions. The observed failure modes aligned with the MC2010, where lower a/d ratios led to shear cracking and higher ratios resulted in more brittle failures. This underscores the importance of incorporating these factors into design practices for HSC beams.

4 Conclusions

In this study, the effect of a/d and longitudinal tensile reinforcement ratios on the shear behavior of HSC beams has been investigated. The experimental values of shear strength from the two-point loading test are compared with the predicted values of the most commonly used design codes and empirical models. Although in the present study, the number of beams tested was quite small for developing a new and effective shear prediction model, the values of shear strength determined by the experimental results compared with different design codes and shear prediction models have provided some insights into the shear behavior of HSC beams. From a comparison of the results, the following conclusions have been drawn:

- The HSC beams without shear reinforcement have failure modes like those of the NSC beams without shear reinforcement, and these failure modes depend on the longitudinal reinforcement ratio and a/d as they affect the mechanisms of shear transfer.
- The shear-span to effective depth ratio (a/d), longitudinal tensile reinforcement ratio (ρ), and aggregate interlock are considered in many design codes and models. However, our findings show that these models often underestimate or overestimate shear resistance capacity by up to 50%, especially in high-strength concrete (HSC) applications, where unique behaviors can lead to brittle failure modes. The Zsutty Model is an exception, offering more accurate predictions. Thus, a thorough understanding of the assumptions and limitations of these models is crucial for accurate shear strength predictions in HSC construction.
- The incorporation of the Model Code 2010 (MC2010) provisions has significantly enhanced the understanding of shear behavior in high-strength concrete (HSC) beams. The experimental results highlight the critical importance of considering the shear-span to effective depth ratio (a/d) and the longitudinal tensile reinforcement ratio (ρ) in shear strength predictions for HSC applications. Adhering to the MC2010 guidelines can lead to more accurate predictions of shear capacity and failure modes, contributing to safer design practices. This study emphasizes the need for ongoing research to refine shear strength prediction models in accordance with the MC2010, addressing the unique challenges posed by HSC structures.

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References

- [1] AROWOJOLO, O. – IBRAHIM, A. – ALMAKRAB, A. – SARAS, N. – NIELSEN, R.: Influence of Shear Span-to-Effective Depth Ratio on Behavior of High-Strength Reinforced Concrete Beams. *International Journal of Concrete Structures and Materials*. Vol. 15, 2021, pp. 1–12.
- [2] DELPHI, H. R. – SULTAN, W. H. – ZGHAIR, L. A.: Comparison Between the Behavior of Reinforced Concrete Beams and RPC Beams Under Bending and Torsion Moments. *Civil and Environmental Engineering*. Vol. 20, No. 1, 2024, pp. 180–193. DOI: 10.2478/cee-2024-0015.
- [3] JAYASINGHE, T. – GUNAWARDENA, T. – MENDIS, P.: Aggregate Interlock in Fractured Concrete Mesoscale Models: A Novel Finite Element Modelling Approach. *Journal of Engineering Mechanics*. Vol. 22, No. 4, 2022. DOI: 10.1007/s43452-022-00488-4.
- [4] ALQARNI, A. S. – et al.: The Effect of Coarse Aggregate Characteristics on the Shear Behavior of Reinforced Concrete Slender Beams. *Construction and Building Materials*. Vol. 264, 2020, p. 120189.
- [5] KHAN, A. – SHAHZAD, A. – SHAHZAD, A. – HANIF, U. – ISRAR, D.: Effect of Lift Core Wall Location in High Rise Buildings.
- [6] GANDEL, R. – JERABEK, J. – MARCALIKOVA, Z.: Reinforced Concrete Beams Without Shear Reinforcement Using Fiber Reinforced Concrete and Alkali-Activated Material. *Civil and Environmental Engineering*. Vol. 19, No. 1, 2023, pp. 348–356. DOI: 10.2478/cee-2023-0031.
- [7] HAYAT, K. – MEHBOOB, S. – BUX, Q. – QURESHI, L. – ALI, A.: Statistical Subspace-Based Damage Detection and Jerk Energy. 2023.
- [8] BEEBY, A. W. – NARAYANAN, R.: *Designers' Guide to EN 1992-1-1 and EN 1992-1-2. Eurocode 2: Design of Concrete Structures: General Rules and Rules for Buildings and Structural Fire Design*. Thomas Telford, 2005.
- [9] MOLUDI, F. – KHEYRODDIN, A.: Comparison of Reinforced Concrete Beam-Column Connections Design Regulations Based on Different RC Codes (ACI 318-2014, National Building Code, and ABA). *Journal of Concrete Structures and Materials*. Vol. 1, No. 1, 2016, pp. 23–41.
- [10] FÉDÉRATION INTERNATIONALE DU BÉTON (fib): *Model Code for Concrete Structures*. Ernst & Sohn, Berlin, 2010.
- [11] SIA: *Construction en béton (Concrete Construction—in French)*. Société Suisse des Ingénieurs et Architectes Ed., 2012.
- [12] PARK, R. – PAULAY, T.: *Reinforced Concrete Structures*. New York: Wiley, 1975.
- [13] KANI, G.: The Riddle of Shear Failure and Its Solution. *Reinforced Concrete Design*. Vol. 27, 1964, The Ronald Press Co., New York.
- [14] GHALI, A. – FAVRE, R. – ELBADRY, M.: *Concrete Structures*. 4th ed. New York: Taylor and Francis, 2012.
- [15] BRESLER, B. – MACGREGOR, J. G.: Review of Concrete Beams Failing in Shear. *Journal of the Structural Division*. Vol. 93, No. 1, 1967, pp. 343–372.
- [16] CLARK, A. P.: Diagonal Tension in Reinforced Concrete Beams. *Journal Proceedings*. 1951.
- [17] ROMBACH, G. – HENZE, L.: Shear Capacity of Concrete Slabs Without Shear Reinforcement Under Concentrated Loads Close to Support. In *High Tech Concrete: Where Technology and Engineering Meet*. Springer, 2018, pp. 676–683.
- [18] KANI, G. N. J.: How Safe Are Our Large Reinforced Concrete Beams? *Journal Proceedings*. 1967.
- [19] GERGES, N. – ISSA, C. A. – SLEIMAN, E. – NAJJAR, M. – KATTOUF, A.: Experimental Study of the Shear Behavior of RC Beams Strengthened with High-Performance Fiber-Reinforced Concrete. *International Journal of Concrete Structures and Materials*. 2023. DOI: 10.1186/s40069-023-00582-8.
- [20] VEGERA, P. – VASHKEVYCH, R. – KHMIL, R. – BLIKHARSKYY, Z.: The Improved Design Method of Shear Strength of Reinforced Concrete Beams Without Transverse Reinforcement. *Scientific Papers of the Journal of Civil Engineering*. Vol. 12, No. 2, 2017, pp. 39–45. DOI: 10.1515/sspjce-2017-001.
- [21] ALHAMAD, S. – et al.: Effect of Shear Span-to-Depth Ratio on the Shear Behavior of BFRP-RC Deep Beams. In *MATEC Web of Conferences*. EDP Sciences, 2017.
- [22] CHEN, S. – LI, J.: Shear Behavior of Reinforced High-Strength Concrete Beams. *ACI Structural Journal*. Vol. 110, No. 6, 2013, pp. 1112.

- [23] HU, B. – WU, Y.-F.: Effect of Shear Span-to-Depth Ratio on Shear Strength Components of RC Beams. *Engineering Structures*. Vol. 168, 2018, pp. 770–783.
- [24] LOPES, A. V.: Revisiting Cracking in Reinforced Concrete Beams: An Updated Analysis. *Applied Sciences*. 2023.
- [25] PERERA, S. – MUTSUYOSHI, H.: Shear Behavior of Reinforced High-Strength Concrete Beams. *ACI Structural Journal*. Vol. 110, No. 1, 2013.
- [26] HAMODA, A. – et al.: Experimental and Numerical Assessment of Reinforced Concrete Beams with Disturbed Depth. *International Journal of Concrete Structures and Materials*. Vol. 13, No. 1, 2019, pp. 1–28.
- [27] DIXON, D. E. – et al.: Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91). *American Concrete Institute (ACI)*, Farmington Hills, 1991.
- [28] ZHANG, J. – LI, S. – XIE, W. – GUO, Y.: Experimental Study on Shear Capacity of High-Strength Reinforced Concrete Deep Beams. 2020.
- [29] QING, L. – YU, K. – MU, R. – FORTH, J. P.: Uniaxial Tensile Behavior of Aligned Steel Fibre Reinforced Cementitious Composites. *Materials and Structures*. Vol. 5, 2019, pp. 1–12. DOI: 10.1617/s11527-019-1374-5.
- [30] MIMURA, Y. – YOSHITAKE, I. – ZHANG, W.: Uniaxial Tension Test of Slender Reinforced Early Age Concrete Members. *Materials*. Vol. 4, No. 8, 2011, pp. 1345–1359. DOI: 10.3390/ma4081345.