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Shear In Reinforced Concrete Beams: A Critical Review Of Theoretical Models, Design Codes And The Influencer Of Mechanical Parameters

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Abstract:
Background*: This article presents a critical review of shear mechanisms in reinforced concrete beams, addressing theoretical models, technical design codes, and influential parameters such as concrete compressive strength (f'_c), transverse reinforcement ratio (ρ_w) and arching action (a/d).*

Materials and Methods*: The literature review highlights the complexity of the phenomenon due to the material's heterogeneity and the interaction of multiple mechanical factors.*

Results*: Experimental studies, such as those by Cladera & Marí and Ismail, show that high-strength concrete (f'_c>70 MPa) requires greater attention to confinement, while short beams (a/d <2,5) exhibit up to a 20% increase in strength due to the arching effect. The ACI 318, EUROCODE 2, and AASHTO LRFD design codes were compared, revealing limitations: ACI underestimates the capacity of beams with high f'_c AASHTO is overly conservative for short beams, and EUROCODE 2 proves to be inaccurate for high transverse reinforcement ratios.*

***Conclusion:** It is concluded that the integration of empirical and numerical models, combined with the updating of design codes, is essential for safe and economical structural designs. This work contributes to both academic and practical discussions, highlighting the need for future research on size effects, aggregate stiffness, and new reinforcement technologies.*

Key Word: *Shear; Beam; Concrete; Building Code.*

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I. Introduction

The development of new materials and the application of new calculation methods to rationalize the design and structural verification of the ultimate limit state are progressing alongside the goal of characterizing the behavior of internal forces. Therefore, the creation of theoretical, empirical, or numerical models capable of accurately and safely determining the mechanical capacity of structural elements enables shorter timelines and reduced costs in the execution of structural design and retrofitting.

When analyzing shear in homogeneous solids under the linear-elastic state of the material, one observes a stress and strain distribution that is easily applicable. However, the macroscopic understanding of composite materials such as reinforced concrete reveals that the mechanical nonlinearity and behavior of the material result in a model of significant mathematical complexity when theoretically estimating the failure load.

According to Cavagnis[1], unidirectional shear in concrete beams has been recognized for over a century as one of the most complex and fundamental topics in structural engineering. This is largely due to the influence of approximately 20 factors, which, according to Leonhardt & Mönnig[2] govern shear strength as a result of the heterogeneity of concrete.

According to Collins[3] there has been a growing demand for research, the establishment of design codes, and the development of formulas to describe the behavior of shear in beams since the 19th century, as illustrated in Figures 1 and 2.

Figure 1: Design models published in the ACI Structural Journal (COLLINS et al., 1996).

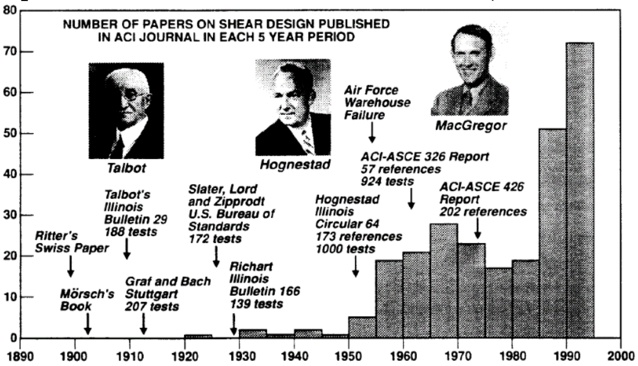

Figure 2: Formulas used in the ACI code[3]

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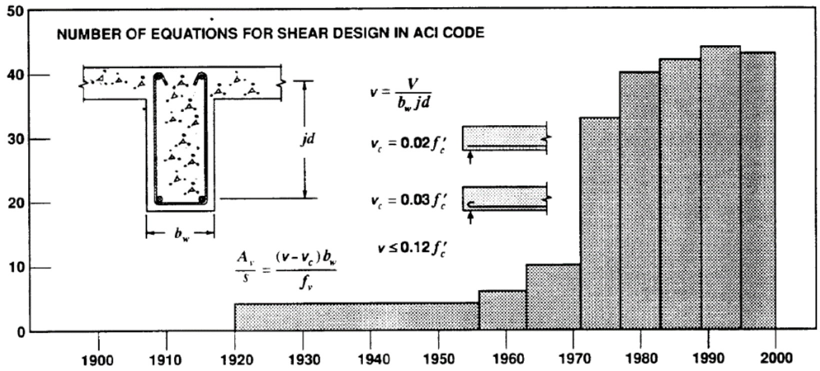
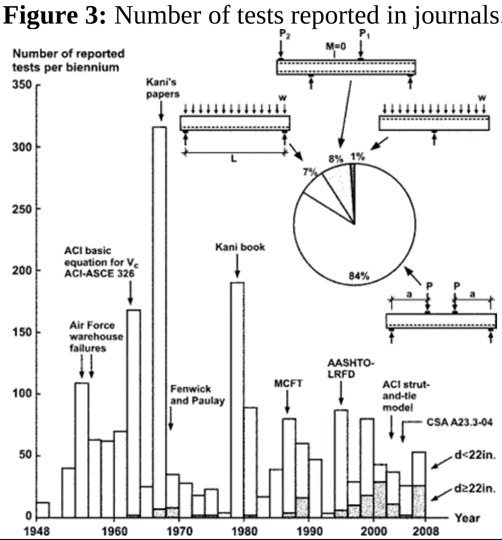


Figura Error! No text of specified style in document.**.1 - Fórmulas utilizadas na norma ACI[3].**

Collins[4] emphasize the number of experimental studies published in major journals over the past 60 years, as well as the predominant loading method for beams, which is mostly represented by four-point bending tests, as shown in Figure 3.

Figure 3: Number of tests reported in journals.



II. Material And Methods

This study adopted a systematic literature review to analyze shear mechanisms in reinforced concrete beams, focusing on theoretical models, technical standards (ACI 318, EUROCODE 2, AASHTO LRFD), and critical parameters (f'_c, a/d, ρ_w). Data collection included scientific articles (from Scopus and Web of Science) and technical codes, selecting 72 studies after a rigorous screening process (excluding works on other elements or unconventional materials).

The analysis categorized the studies into three main areas: theoretical models (e.g., Ritter-Mörsch truss model), mechanical parameters (e.g., arching action), and code comparison. Experimental data (e.g., failure loads) were contrasted with theoretical predictions and the ratio $V_{\exp}/V_{teo}$. For instance, it was found that ACI 318 underestimates strength for f'_c>70MPa, while AASHTO LRFD is overly conservative for short beams.

III. Result And Discussion

Shear Force Transfer

Based on a homogeneous prismatic beam, simply supported, made of linear-elastic material and subjected to loads perpendicular to its longitudinal axis, the transfer of normal stresses tangential to the transverse axis occurs, as illustrated in Figures 4 and 5. It is noteworthy that these tension and compression forces, which arise parallel to each other, define the progressive increase in shear forces. These stresses cancel out at the top and bottom edges, reach a maximum at the neutral axis, and tend to cause sliding at the interfaces in non-monolithic elements. These normal bending stresses (σ) and shear stresses (τ) result in a biaxial stress state, giving rise to inclined planes in accordance with solid mechanics principles.

Figure 4: Simply supported beam: (a) stresses in the x-y planes, (b) and principal plane (c).

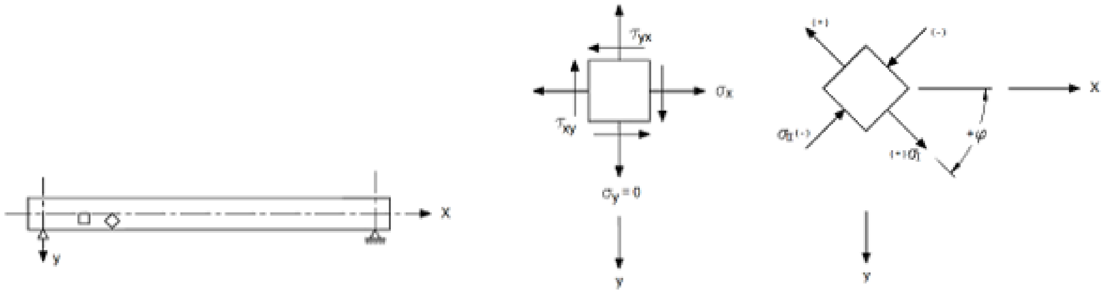
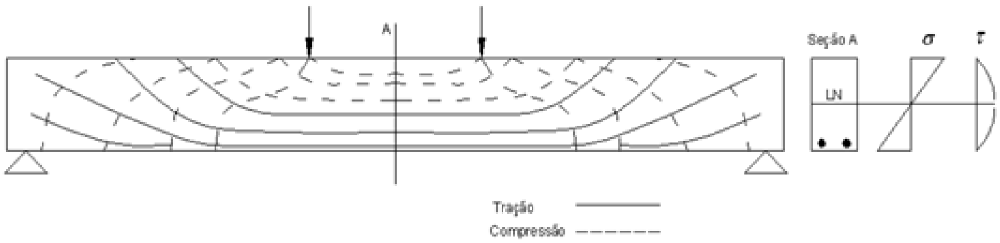


Figure 5: Principal Stress Planes in Uncracked Beams

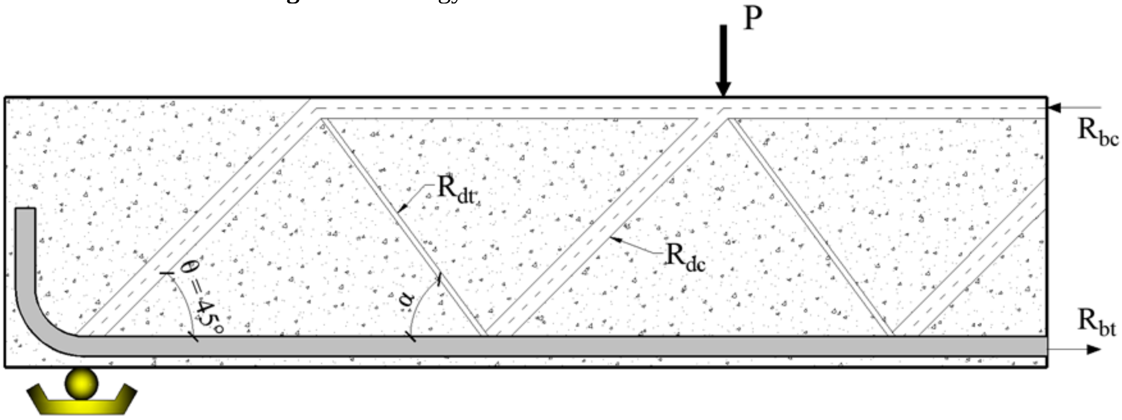


Concrete beams, with the progressive increase in loading, exhibit three distinct modes of stress and strain distribution along the longitudinal section. Initially, Stage I occurs, which is where the design of beams for serviceability should remain. In this stage, the acting stresses do not exceed the tensile strength of the concrete—meaning the beam remains uncracked. Stage II is considered the serviceability limit state, where the applied stresses are still within the elastic range of steel or concrete, but initial cracking and small deformations begin to appear. When the beam exhibits excessive deflections—greater than 0.4% of the span—and deformations surpass the elastic limit of steel and concrete, it is considered Stage III, which corresponds to the ultimate limit state, leading to collapse after further loading.

Ritter-Mörsch Classic Truss Model

Based on an analogy of internal force transfer within the beam, Ritter and Mörsch[5] developed a shear design and verification model. As shown in Figure 6, the load transfer is represented through compressed diagonals (struts), tensioned diagonals (ties), and top and bottom chords responsible for the tension and compression forces resulting from flexure in the beam.

Figure 6: Analogy of the Ritter-Mörsch[5] Classic Truss



Where:

R_{dc} : Resistance of the compressed diagonal (strut);

R_{dt} : Resistance of the tensioned diagonal (tie);

R_{bc} : Resistance of the compressed chord (compressed concrete);

R_{bt} : Resistance of the tensioned chord (longitudinal reinforcement);

θ : Inclination angle of the strut;

α : Inclination angle of the tie.

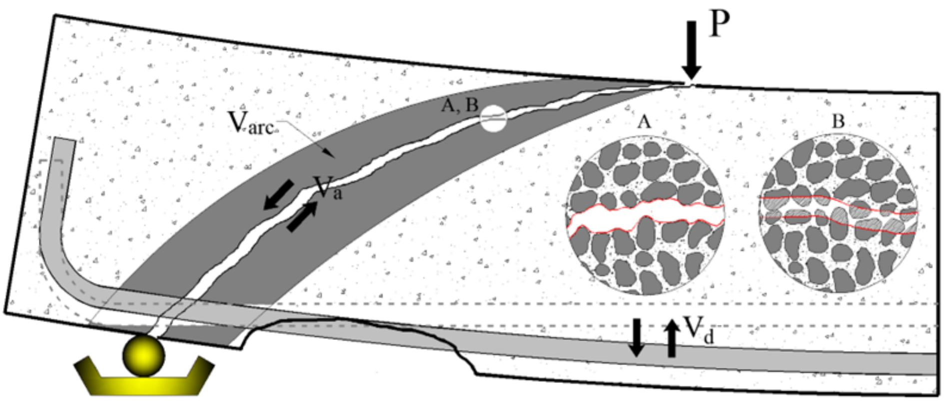
Main Characteristics of the Classic Model:

- The truss is considered isostatic;
- Internal forces are aligned with the diagonals and chords;
- Struts are inclined at 45° relative to the chords, while ties have variable angles;
- The ties represent the combined tensile resistance of the concrete and the transverse reinforcement, such as stirrups.

Shear Force Transfer After Cracking

Following a linear analysis of shear forces using the Ritter-Mörsch[5] truss model, the post-cracking resistance behavior becomes a major concern from the perspective of ultimate strength. This is due to the non-linearity in stress redistribution along the longitudinal section of concrete beams. Thus, Figure 5 illustrates several phenomena that begin with the onset of cracking.

Figure 7: Shear Force Transfer After Cracking



Aggregate Interlock (V_a):

Through sliding along the interfaces of shear cracks, interlocking may occur between coarse aggregates. This aggregate interlock is, on a unit basis, associated with increased shear strength in the beam[6,7]. However, it should be noted that the crack plane, as illustrated in Figure 5, can follow two different patterns[8,9].

- **Crack Pattern A**: where the crack propagates through coarse aggregates, is typical when the concrete has compressive strength below 70 MPa Bentz[10], as the stiffness of the cementitious matrix is lower than that of the aggregates, leading to the fracture of the aggregate–paste interface.
- **Crack Pattern B:** is observed in high-strength concrete or in concretes with flaky aggregates. In the first case, the mortar has greater bonding capacity with the aggregates. In the latter, failure tends to occur through bending of the flaky aggregates, regardless of the compressive strength of the concrete.

Dowel Action (V_d):

This phenomenon arises from the difference in stiffness between the longitudinal reinforcement and the concrete. The ability of the reinforcement to resist forces perpendicular to the beam axis can, according to Gergely[11], Houde[12] and Sonnenberg & Al-Mahaidi[13], contribute between 18% and 26% to the total shear resistance. Cavagnis[1] suggest that this effect can be quantified using an empirical model and is directly influenced by the concrete's tensile strength, longitudinal reinforcement ratio, bar diameter, and spacing.

Arching Action (V_{arc}):

Arching action becomes more significant when the ratio of shear span to effective depth (a/d) is less than 2.5. In such cases, the strut tends to form an arch with the top chord (compressed zone), resulting in increased ultimate shear strength. This phenomenon is commonly observed in deep beams, corbels, and foundation blocks.

Cladera & Marí[14]

The aim of the study was to investigate the influence and efficiency of high-strength concrete (f'_c) in beams with and without stirrups. The research included four concrete strength classes: H50 ($f'_c = 49{,}9$ MPa), H60 ($f'_c = 60{,}8$ MPa), H75 ($f'_c = 68{,}9$ MPa) and H100 ($f'_c = 87$ MPa) Experimental results were compared against predictions from AASHTO LRFD[15], EUROCODE 2[5], ACI 318[16] and empirical models proposed by the authors. The beams were tested using a three-point bending setup and loaded to failure. Figures 8 and 9 below present the details of the experimental program.

Figure 8: Test Setup, Cladera & Marí[14]

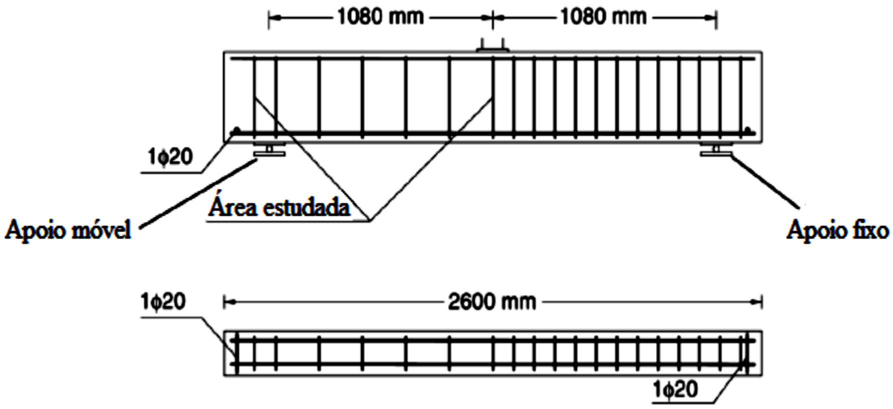
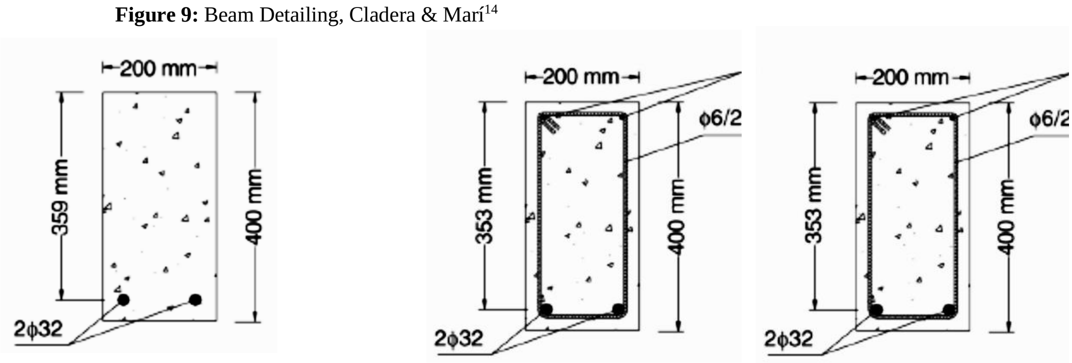
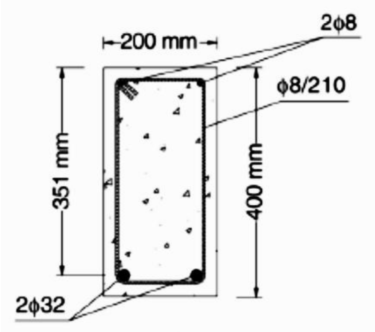


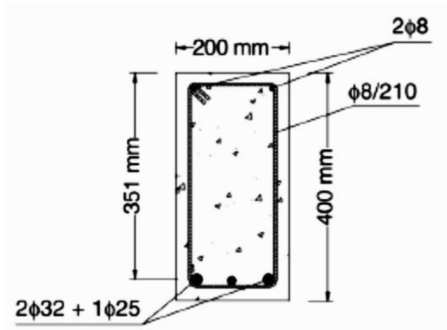
Figure 9: Beam Detailing, Cladera & Marí[14]



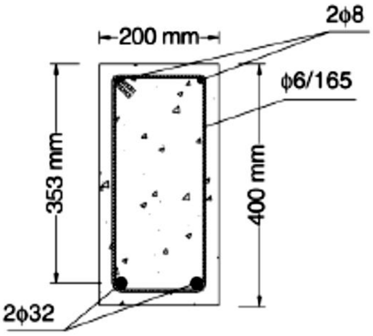
H50/1, H60/1, H75/1, H100/1 H50/2 H60/2, H75/2



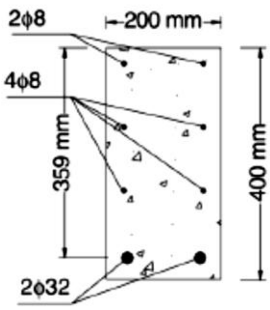
H50/3, H60/3, H75/3, H100/3



H50/4, H60/4, H75/4, H100/4



H100/2



H50/5, H100/5

After the tests, Cladera & Marí[14] observed the following:

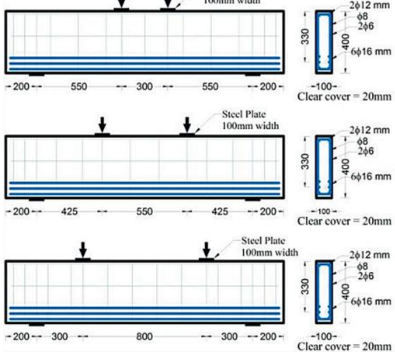
- Beams made of concrete without transverse reinforcement exhibited a progressive increase in brittleness with higher compressive strength;
- Shear strength increased as the f'_c rose;
- Ductility was significantly improved by the presence of transverse reinforcement;
- The efficiency of transverse reinforcement increased with higher concrete compressive strength;
- The empirical models proposed by the authors showed accuracy levels comparable to those of the AASHTO LRFD[15], which is based on the Modified Compression Field Theory (MCFT).

Ismail[17]

This study presents an experimental investigation of 24 short beams, with and without vertical reinforcement, predominantly exhibiting enhanced arching action. Parameters such as the a/d ratio, transverse reinforcement ratio, and concrete compressive strength (f'_c), were studied to assess their influence on mechanical behavior and to compare the performance of various design codes in predicting ultimate shear capacity.

The experimental program consisted of two phases. The first phase, shown in Figure 10, included beams with the same longitudinal reinforcement ratios and cross-sectional dimensions. The variables included shear span to effective depth ratios (1,67, 1,29, 0,91), concrete compressive strength ranging from 30 MPa to 85 MPa, skin reinforcement ratio (ρ_s) (0% e 0,215%) and transverse reinforcement ratio (ρ_v) (ranging from 0% e 1,44%).

Figure 10: First Phase of the Experimental Program[17]



The second phase focused on analyzing the *size effect* in short beams without shear reinforcement, by varying the effective depth while maintaining a constant a/d ratio. The concrete compressive strength was kept around 30 MPa. The detailing of this phase is shown in Figure 11.

Figure 11: Second Phase of the Experimental Program[17]

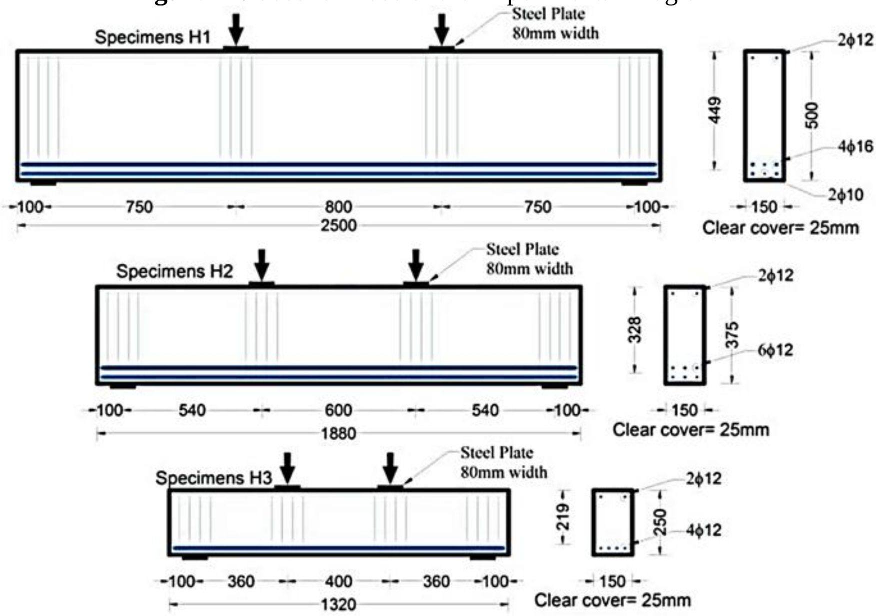


Table 1: presents the characteristics of the tested beams, including their failure loads.

Table 1: Properties of the Tested Beams (Adapted from Ismail[17])

Beam	Phase	a/d	f'_c (MPa)	ρ_v (%)	ρ_s (%)	Failure Load (kN)
A1	I	1,67	85,2	0	0	353
A2		1,67	85,7	0,56	0,215	422
A3		1,67	85,1	1,26	0,215	466
B1		1,29	86,9	0	0	491
B2		1,29	86,6	0,59	0,215	564
B3		1,29	88,1	1,34	0,215	567
C1		0,91	85,7	0	0	741
C2		0,91	85,8	0,67	0,215	>920*
C3		0,91	86,0	1,44	0,215	>920*

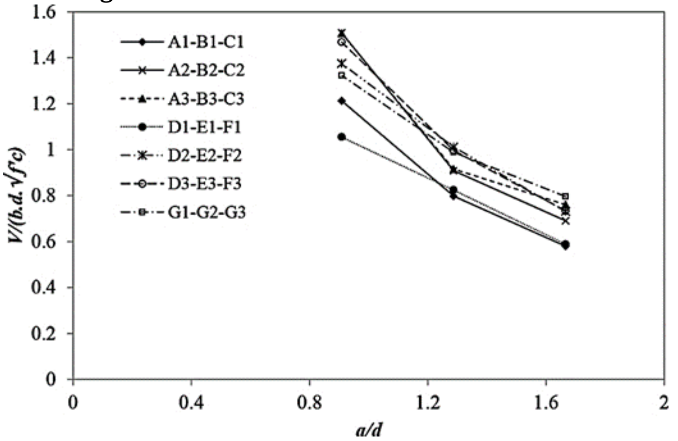
Table 2: Properties of the Tested Beams (Adapted from Ismail[17]) (Cont.)

Beam	Phase	a/d	f'_c (MPa)	ρ_v (%)	ρ_s (%)	Failure Load (kN)
D1	I	1,67	58,8	0	0	296
D2		1,67	59,7	0,56	0,215	373
D3		1,67	58,1	1,26	0,215	369
E1		1,29	58,2	0	0	415
E2		1,29	59,1	0,59	0,215	513
E3		1,29	59,2	1,34	0,215	506
F1		0,91	60,5	0	0	545
F2		0,91	60,6	0,67	0,215	706
F3		0,91	59,5	1,44	0,215	748
G1		1,67	30,9	0,56	0,215	292
G2		1,29	30,5	0,59	0,215	372
G3		0,91	31,3	0,67	0,215	489
H1	II	1,67	35,8	0	0	375
H2		1,65	35,8	0	0	316
H3		1,64	35,8	0	0	254

*The capacity of the testing machine was reached before failure.

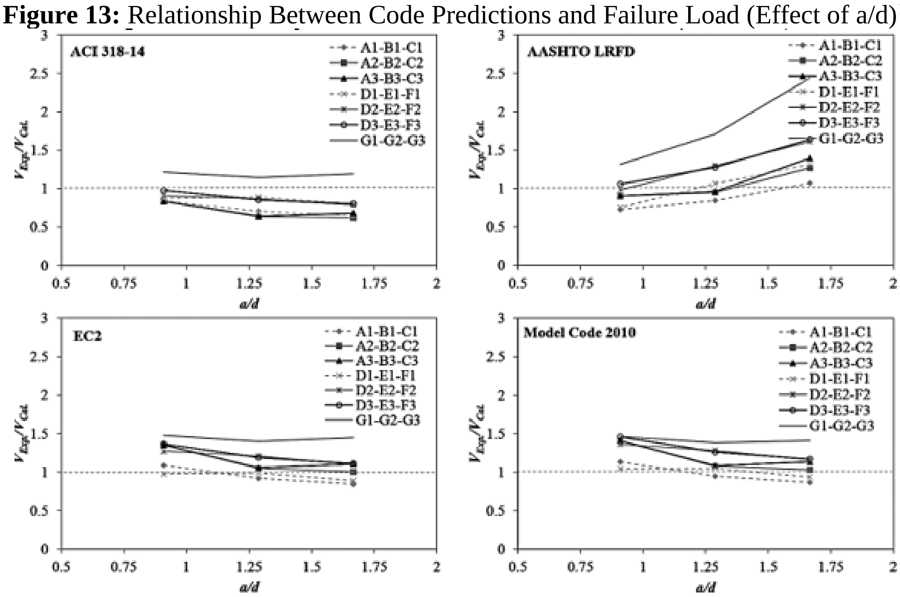
From the analysis of the a/d ratio, it was confirmed that an increase in the shear span leads to a reduction in the stresses acting on the strut, thereby decreasing the shear strength of the beam, as illustrated in Figure 12.

Figure 12: Influence of a/d on Failure Load[17]



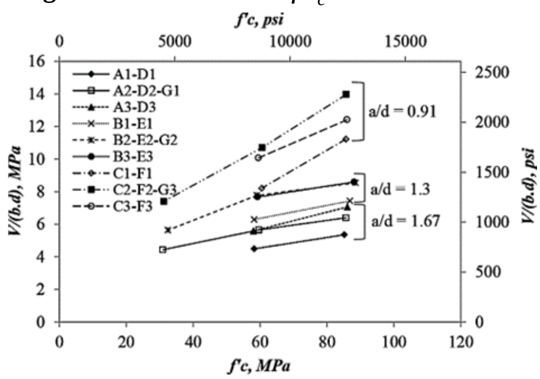
It was observed that ACI 318[16] falls below an appropriate safety margin. AASHTO LRFD[15] tends to be significantly conservative as the a/d ratio decreases. MODEL CODE and EUROCODE 2[5] show conservative behavior with increasing f'_c and ρ_v , as shown in Figure 4.10.

Figure 13: Relationship Between Code Predictions and Failure Load (Effect of a/d)[17]



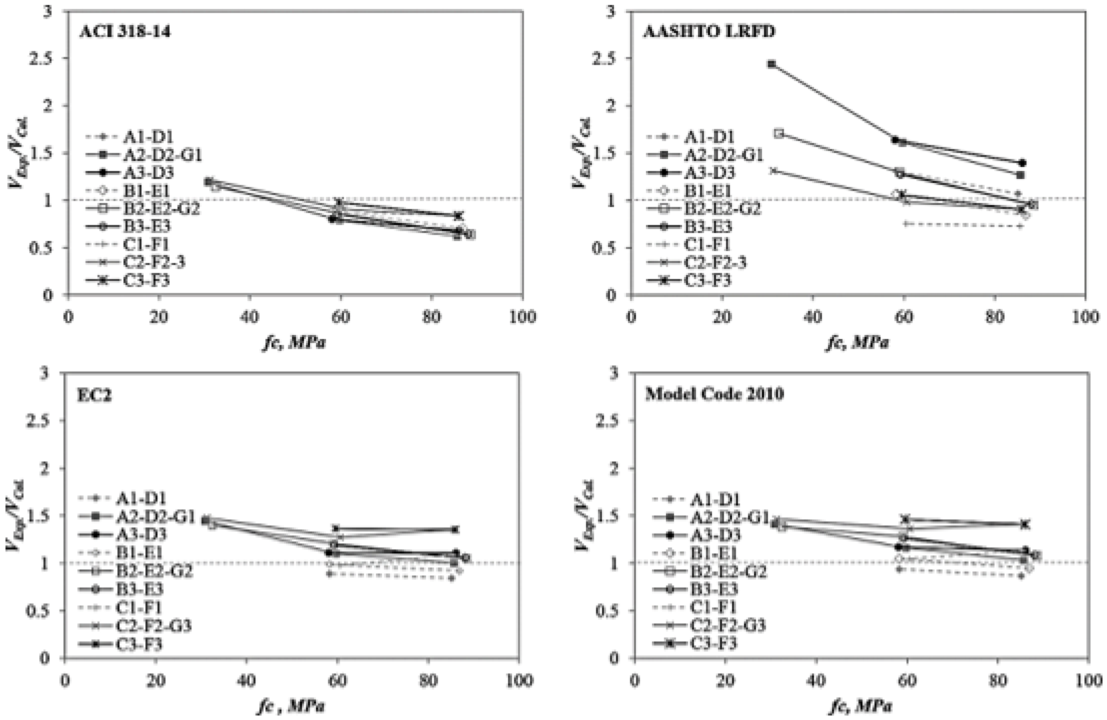
When analyzing the increase in f'_c , there was a corresponding increase in shear strength as the a/d , ratio decreased. According to Figure 14 the author highlights that the influence of the arching effect is directly related to the increased stiffness of the strut.

Figure 14: Influence of f'_c on Failure Load[17]



It is noted that the accuracy of the design codes tends to decrease in the ratio between experimental and theoretical values. ACI 318[16] shows greater accuracy for f'_c around 30 MPa but becomes unsafe for higher values, likely due to the theoretical model being limited to f'_c below 69 MPa, as shown in Figure 15.

Figure 15: Relationship Between Code Predictions and Failure Load (Effect of f'_c)[17]



The addition of 0.6% transverse reinforcement increased the shear capacity by approximately 20%. This can be attributed to the fact that the reinforcement helps confine the interfaces as they tend to slide, as illustrated in Figure 16.

Figure 16: Influence of ρ_v on Failure Load[17]

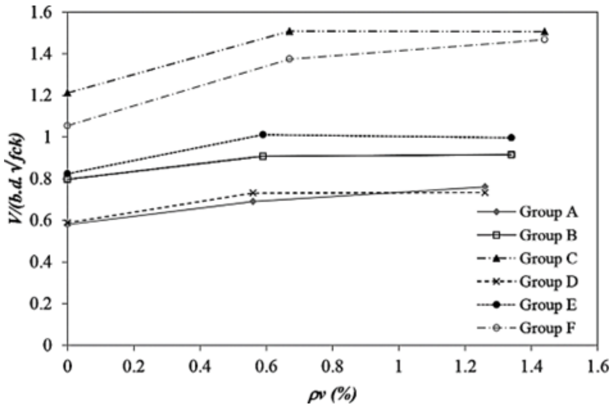
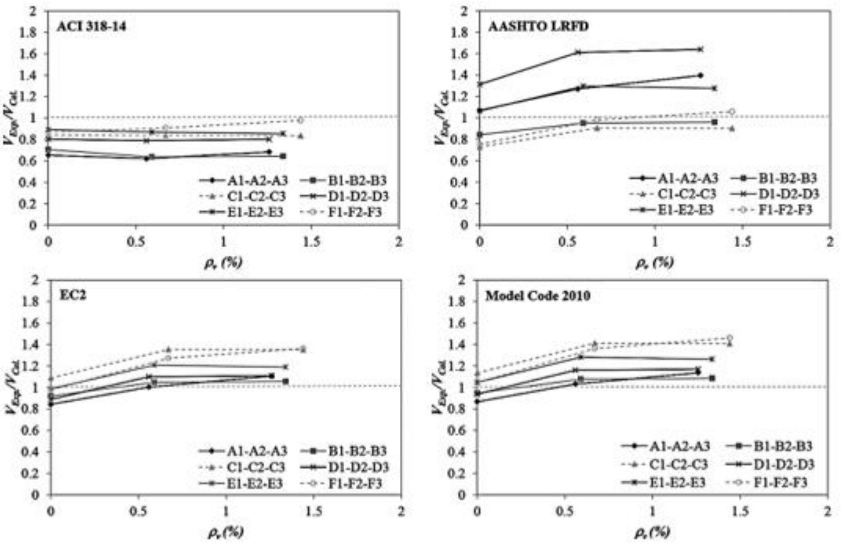


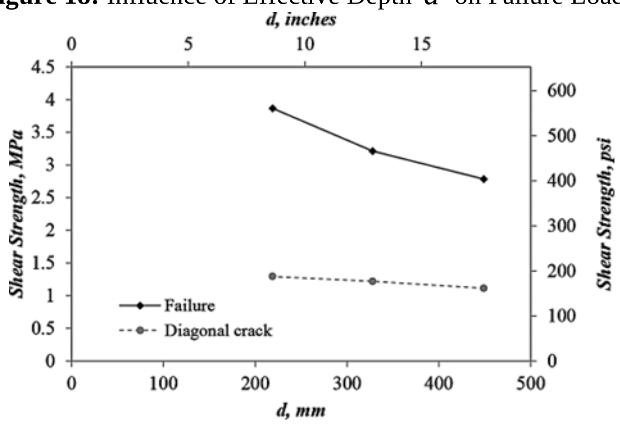
Figure 17 shows that ACI 318[16] remains approximately constant when the transverse reinforcement ratio is varied. It can be inferred that vertical reinforcement is properly accounted for in the code, and deviations from appropriate safety levels in the theoretical predictions are primarily due to the influence of the arching effect. In contrast, other design codes are affected by being noticeably conservative.

Figure 17: Relationship Between Code Predictions and Failure Load (Effect of ρ_v)[17]



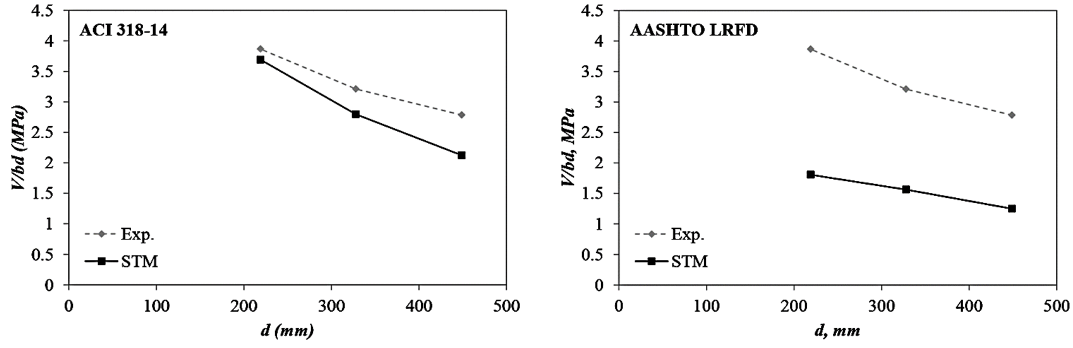
To evaluate the performance of Strut-and-Tie Models (STM) in design codes with respect to the size effect, the authors found, as shown in Figure 18, that the phenomenon observed by Bažant & Kim[18] demonstrates a reduction in strength with increasing effective depth.

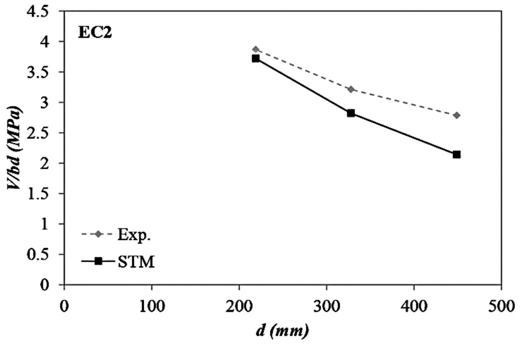
Figure 18: Influence of Effective Depth d on Failure Load[17]

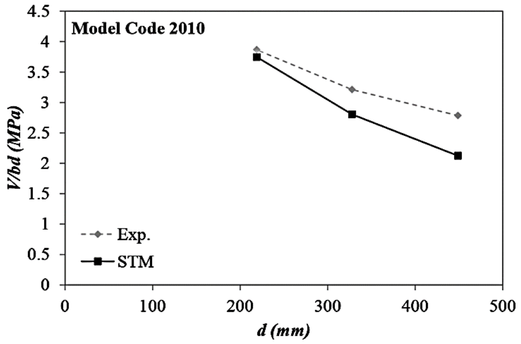


In Figure 19, ACI 318[16], EUROCODE 2[5] and MODEL CODE exhibited increasing inaccuracy in predicting failure loads, which was even more pronounced in AASHTO LRFD[15] due to its disregard for the size effect.

Figure 19: Relationship Between Code Predictions and Failure Load (Effect of d)[17]







Based on the results and analyses described above, the authors concluded that:

- The arching effect is the most significant parameter when $a/d < 2,5$;
- The influence of concrete compressive strength is more prominent in short beams, and vertical reinforcement is essential for confinement, crack control, and strength enhancement;
- The size effect has little impact on shear cracking behavior.

IV. Conclusion

This article reviewed the shear mechanisms in reinforced concrete beams, with an emphasis on the influence of parameters such as concrete strength (f'_c), transverse reinforcement ratio (ρ_w) and arching action (a/d <2,5). The experimental studies by Cladera & Marí[14] and Ismail[17] demonstrated that:

1. **High-Strength Concrete** (f'_c>70 MPa): Brittleness increases in the absence of stirrups, requiring greater attention to confinement. Standards such as ACI 318 underestimate the ultimate strength in these cases, limiting their provisions to f'_c≤69 MPa.
2. **Arching Action: Short beams** (a/d <2,5) exhibit up to a 20% increase in strength due to the stiffness of the compressed strut, a phenomenon not fully accounted for by AASHTO LRFD, which proved to be overly conservative.
3. **Transverse Reinforcement:** The addition of 0.6% stirrups increased shear capacity by 20%, validating their importance in crack control and stress redistribution.

The analyzed standards (ACI 318, EUROCODE 2, AASHTO LRFD) revealed gaps in specific scenarios:

- ACI 318 is accurate for f'_c≈30 MPa but inadequate for high-strength concrete.
- AASHTO LRFD partially disregards the arching effect, leading to overdesign of short beams.
- EUROCODE 2 proved to be conservative for high transverse reinforcement ratios.

It is recommended to integrate empirical and numerical models (such as the Modified Compression Field Theory) to expand the applicability of design standards. Future studies should explore the interaction between coarse aggregates, size effects, and new reinforcement techniques, aiming to optimize the balance between safety and economic efficiency in structural design.

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