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Evaluating and Improving the ACI 318-19 Shear Strength Relationships for Seismic Design of Reinforced Concrete Columns

A thesis submitted in partial satisfaction of the
requirement for the degree Master of Science
in Civil Engineering

by

Alex-Amirnezam Fakhroo

2022

ABSTRACT OF THE THESIS

Evaluating and Improving the ACI 318-19 Shear Strength Relationships for Seismic Design of Reinforced Concrete Columns

by

Alex-Amirnezam Fakhroo
Master of Science in Civil Engineering
University of California, Los Angeles, 2022

Professor John Wright Wallace, Chair

The ACI 318-19 provisions for computing the one-way shear capacity of non-prestressed reinforced concrete (RC) columns are primarily based on the results obtained from the RC beams. These equations were introduced in ACI 318-19 to account for the effects of the longitudinal reinforcement ratio, the depth of the column, and the applied axial load on the overall shear capacity. In this study, a column database was developed and used to evaluate the accuracy of the one-way shear provisions. Then, the ACI 318-19 shear capacity equations were evaluated by using the test results for non-prestressed RC columns. The results showed that these relationships significantly underpredict the actual shear capacity of the columns obtained from the test results. To improve the accuracy of the shear capacity equations, a new relationship is proposed and discussed in detail.

The thesis of Alex-Amirnezam Fakhroo is approved.

Henry J. Burton

Thomas A. Sabol

John Wright Wallace, Committee Chair

University of California, Los Angeles
2022

To my parents.

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Abbreviations

ACI	American Concrete Institute
ALR	Axial Load Ratio
CV	Coefficient of Variation
MF	Moment Frame
OWS	One-way Shear
RC	Reinforced Concrete
RMSE	Root Mean Square Error
SSR	Shear Span Ratio
SR	Shear Strength

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Chapter 1: Introduction

1.1 General

In ACI 318-19, the relationships for calculating the shear capacity of reinforced concrete (RC) columns were updated to account for the effects of the longitudinal reinforcement ratio, the depth of the column, and the applied axial load on the overall shear capacity. However, the test results from a beam database were primarily used for developing these relationships.

To properly evaluate the accuracy of the predicted shear capacity of non-prestressed RC columns, a database has been developed based on the available shear test results for RC concrete columns.

In this study, the ACI 318-19 shear capacity relationships are evaluated using the data recorded in the developed column database and the proposed changes are discussed.

1.2 Background

The general philosophy for predicting the one-way shear (OWS) strength of RC members (non-prestressed) was largely unchanged since the 1963 revision of ACI code (ACI Committee 318 1963). The general form of the relationship for computing the OWS strength for RC members (non-prestressed) by ACI 318-14, V_n , is the sum of the contribution from the concrete (V_c) and the contribution from the transverse reinforcement (V_s) (ACI 318, 2014).

When V_c was initially introduced into ACI, nearly a century ago, it was defined as a fraction of the concrete compressive strength, f_c', multiplied by the width and depth of the member cross-section (Kuchma et al., 2019). A revised form of the equation was introduced later in ACI 318-63 to estimate the diagonal cracking strength (Kuchma et al., 2019). Eventually, the presented relationship for computing V_c was made proportional to the square root of the concrete compressive strength. Additional terms were added to the V_c equation in ACI over time to account for the effects of applied moment, axial load, and the longitudinal tension reinforcement ratio.

Relationships in ACI 318-19 for computing the shear capacity in RC members (non-prestressed) had significant changes compared to the relationships in ACI 318-14. The relationships in ACI 318-14, summarized in Table 1 (ACI 318, 2014), were replaced by a general relationship which accounts for the longitudinal reinforcement ratio, ρ_w, and the effect of axial stress in the V_c equation. In addition, a factor for including the effect of member size, λ_s, was introduced for members which are not compliant to the minimum shear reinforcement requirement ($A_v < A_{v,min}$). The size effect factor which is presented as $\sqrt{2/(1+d/10)}$ is dependent on the depth of the member and is limited to a maximum value of 1.0 (ACI 318, 2019). However, the form of the relationship for calculating V_c which includes the size effect factor, do not apply for columns under seismic loads. These columns are required to meet the minimum shear reinforcement. The general forms of the shear capacity relationships are shown in Table 2 (ACI 318, 2019). The V_c relationships in ACI 318-19 for members with transverse reinforcement were developed and empirically validated by laboratory beam tests but used for RC columns as well.

Table 1: ACI 318-14 RC OWS relationships

ACI 318-14 OWS Strength Relationships (Section 22.5)		
Term	**Simplified Approach**	**Detailed Approach**
V_c for members with no axial load	$2\lambda\sqrt{f'_c}b_w d$	$\min\left\{\begin{matrix}\left[1.9\lambda\sqrt{f'_c}+2500\rho_w\frac{V_u d}{M_u}\right]b_w d\\ \left[1.9\lambda\sqrt{f'_c}+2500\rho_w\right]b_w d\\ 3.5\lambda\sqrt{f'_c}\,b_w d\end{matrix}\right\}$
V_c for members with axial load (N_u)	Member with axial compression: $2\lambda\left[1+\frac{N_u}{2000\,A_g}\right]\sqrt{f'_c}\,b_w d$ Member with axial tension: $2\lambda\left[1+\frac{N_u}{500\,A_g}\right]\sqrt{f'_c}\,b_w d$	Member with axial compression: $\min\left\{\begin{matrix}\left[1.9\lambda\sqrt{f'_c}+2500\rho_w\frac{V_u\,d}{M_u-N_u\frac{4h-d}{8}}\right]b_w d\\ \text{equation not applicable if } M_u-N_u\frac{4h-d}{8}<0\\ 3.5\lambda\left[1+\frac{N_u}{500\,A_g}\right]\sqrt{f'_c}\,b_w d\end{matrix}\right\}$
V_s	$A_v\,f_{yt}\frac{d}{s}$	same as the simplified approach
V_n	$V_n=V_c+V_s$	same as the simplified approach

Notes:

1. *The units are in lb., inch, and psi.*
2. *Not all the code limit requirements are indicated.*
3. *s in the V_s equation is the spiral pitch or the longitudinal spacing of the shear reinforcement in the critical zone. (ACI 318, 2014)*

Table 2: ACI 318-19 RC OWS relationships

ACI 318-19 OWS Strength Relationships (Section 22.5)		
Term	**Simplified Approach**	**Detailed Approach**
V_c for members with $A_v \geq A_{v,min}$	$[2\lambda\sqrt{f_c'}+\frac{N_u}{6\ A_g}]\ b_w d$	$\left[8\lambda(\rho_w)^{1/3}\sqrt{f_c'}+\frac{N_u}{6\ A_g}\right] b_w d$
V_c for members with $A_v < A_{v,min}$	$\left[8\lambda_s\lambda(\rho_w)^{1/3}\sqrt{f_c'}+\frac{N_u}{6\ A_g}\right] b_w d$	same as the simplified approach
V_s	$A_v\ f_{yt}\frac{d}{s}$	same as the simplified approach
V_n	$V_n = V_c + V_s$	same as the simplified approach

Notes:

1. *The units are in lb., inch, and psi.*
2. *Not all the code limit requirements are indicated.*
3. *s in the V_s equation is the spiral pitch or the longitudinal spacing of the shear reinforcement in the critical zone.*
4. *Axial load, N_u, is positive for compression and negative for tension.*
5. V_c *shall not be taken less than zero.*
6. V_c shall not be taken greater than $5\lambda\sqrt{f_c'}b_w d$.
7. *The value of $N_u/6\ A_g$ shall not be taken greater than $0.05f_c'$.*
8. *The value of f_{yt} permitted for design calculations shall comply with ACI 318-19 section 20.2.2.4. (ACI 318, 2019)*

1.3 Objectives

The objective of this study is to evaluate the existing ACI 318 relationships for calculating the shear capacity for non-prestressed RC columns, and propose a more accurate relationship, if required. The V_c relationships in ACI 318-19 for members with transverse reinforcement were developed and empirically validated based on laboratory beam tests. However, these relationships are used for RC columns as well. This was due to the lack of a comprehensive database based on column test results. Therefore, the first step to this study was to develop a well-organized database of column test results to be able to accurately evaluate the existing shear strength relationships for RC columns.

In this study more than 150 test results for RC columns were collected. In which about 60 of these specimens were applicable to this study after applying the required filtering. The filters used for selecting the specimens for this study is discussed, in detail, in Chapter 2.

A comparison between the RC column estimated capacity per ACI 318-19 relationships, and the test results shows that these relationships significantly underpredict the actual shear capacity of the columns. To improve the accuracy of the shear capacity equations, a new relationship is proposed by running several regression-analysis models and is discussed in Chapter 4.

1.4 Thesis Organization

This thesis consists of five chapters. **Chapter 2** provides background information on the preparation and the structure of the column database, the references used for the data collection, the recorded key parameters and the filters used for selecting the specimens for this study. **Chapter 3** evaluates the accuracy and safety of the ACI 318-19 relationships and identifies the important parameters in predicting shear strength for RC columns, and discusses the trends found in the comparison between the test results and the predicted values. In **Chapter 4**, the methodology used, and the steps taken for improving the RC columns shear strength relationships are discussed. The proposed changes are explored, and the assumptions and limitations are discussed. **Chapter 5** presents a summary and conclusion of the discoveries as well as possible areas for further improvement in future studies.

Chapter 2: Experimental Database

2.1 General

Through several decades of research studies on the shear capacity of RC members, there have been considerable advancement on the developed relationships for predicting the member capacity. The new provisions for computing the OWS capacity of RC members in ACI 318-19 addressed many of the concerns identified in the previous studies and improved the predicted capacity considerably, especially for RC beams, given the new provisions were developed based on beam shear test results. In order to be able to evaluate the new OWS provisions in ACI 318-19 for predicting the shear capacity of RC columns, a database from column experimental results was required. As part of this thesis, a database based on column test results was developed. More than 150 test specimens were evaluated and the test results for specimens which were applicable to this study were collected. The test results for these specimens were extracted from numerous research papers which their publication year spans from 1989 to 2021.

2.2 Structure of The Column Database

The collected test results were recorded in the database and structured based on the key information needed for the data analysis. The structure of the column database includes the following main sections:

1. General Information: In this section the general information on the journal publication used, including the authors, specimen ID, the publication year and the country are recorded.
2. Loading and Test Set-up: This section includes the information on the applied loading to the specimen.

3. Geometry: Includes the information on the geometry of the specimen, such as the shape of the specimen, and the geometric dimensions.
4. Concrete Material and Construction: The information on the concrete properties is recorded under this section.
5. Retrofit: This section covers the information on retrofitted columns. Retrofitted columns are not applicable to this research. However, this section has been added to develop a more comprehensive database for future studies.
6. Confined Core Dimensions: The information on column confinement is recorded under this section. This information is not directly required for this research. However, it is important for future studies specially for research on the ductility of RC columns in special moment frames.
7. Longitudinal Reinforcement: The information on the properties of longitudinal rebars is recorded in this section. The number of rebars and the size, for calculating the reinforcement ratio, and the rebar yield stress are key parameters for this study under this section.
8. Transverse Reinforcement: The information on the transverse reinforcement is recorded in this section, including the hoop type and the details, crossties type and the details, and the rebar properties.
9. Experimental Results: The test results, including the information required for the backbone curve, and the information on the failure mode, for each specimen, are recorded under this section.

The information on the maximum lateral load and the corresponding displacement, in both, positive and negative directions is crucial for this research. The maximum lateral load and the corresponding displacement can be obtained from the shear-displacement response backbone curves. The backbone curves provide important information on the RC column strength and deformation capacities. The backbone curves, typically have seven important points, including the Origin, Cracking, General Yield, Peak (important in this study), Ultimate, Residual, and Collapse, corresponding to the first cycle at each load-displacement level (Abdullah S. A., 2019) as shown in Figure 1.

10. Flexural Strength: This section covers the information on the flexural strength of the specimen. However, it is not required for this research.
11. Shear Strength: The calculated contributions from the concrete (V_c) and the transverse reinforcement (V_s), using the ACI 318-19 provisions, are calculated and recorded in this section.
12. Notes: This section is designated for including any additional necessary information on the specimens and the test results.

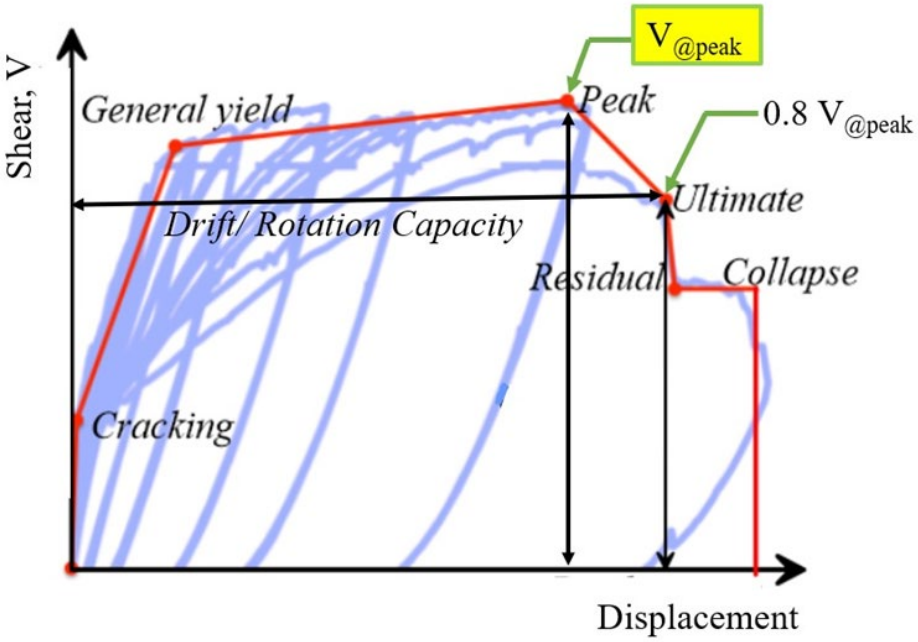

Figure 1: Example of backbone curve (Abdullah & Wallace, 2018)

2.3 Important Parameters

The shear strength of RC columns is assumed to be resisted by the concrete (V_c) and the remainder by the transverse reinforcement (V_s). The shear strength provided by concrete, is considered as the shear causing inclined cracking in the member. Once the cracking occurs, the concrete contribution to the overall shear strength is attributed to aggregate interlock, dowel action, and the shear transmitted across the area under compression. (ACI 318, 2019)

The nominal shear capacity in ACI 318 is defined as the summation of the nominal shear resistance by the concrete and steel, as discussed above, which has the following relationship (ACI 318, 2019):

$$V_n = V_c + V_s$$

The design shear strength of the member, $\emptyset V_n$, would need to be equal or greater than the factored shear force. The design shear strength requires the application of the reduction factors, $\emptyset$, which is 0.75 as defined in ACI 318 (ACI 318, 2019):

$$\emptyset V_n = \emptyset V_c + \emptyset V_s$$

$$V_u \leq \emptyset V_n$$

If the applied shear load, V_u, is divided by effective cross section, $b_w d$, the result will be the average shear stress. This stress is not equivalent to the diagonal tension stress. It is merely an indicator for the magnitude of shear (Jack C. McCormac, 2015).

The shear strength of the member is based on the average shear over the effective cross section, $b_w d$ (ACI 318, 2019). The key parameters that contribute to the overall shear strength of RC columns (briefly introduced in section 1.2) are as follows:

2.3.1 Concrete Compressive Strength

The concrete compressive strength, f'_c, is one of the key parameters in predicting the shear strength. The shear strength provided by concrete, V_c, is considered to be an average shear strength (typically is defined as a factor of $\lambda\sqrt{f'_c}$ in ACI 318) times the effective cross section ($b_w d$). As commonly defined in ACI 318, the unit for the square root of specified compressive strength of concrete, $\sqrt{f'_c}$, is psi.

The actual (measured) compressive strength of concrete is typically larger than the specified values. Therefore, in this study, in order to compare the test results with the predicted shear strength more accurately, the measured compressive strength of concrete is used.

2.3.2 Concrete Modification Factor

Concrete modification factor, λ, is another important parameter defined in ACI 318 to reduce the concrete compressive strength when a normal weight concrete is not used. The value of λ for normal weight concrete is taken as 1.0, as permitted per ACI 318-19 clause 19.2.4.3, which is applicable to most of the practical design cases. However, if for any reason, normal weight concrete is not being used, the concrete strength needs to be modified by the application of λ as described in ACI 318-19 section 19.2.4.

2.3.3 Axial Load Ratio

The axial load ratio (ALR) is defined as the ratio of axial load, N_u, over the member cross-sectional area, A_g, and the concrete compressive strength, $N_u/(A_g * f_c')$. The ratio of axial load by cross-sectional area, N_u/A_g, is divided by f_c' to make the ratio unitless (normalized form). The value of N_u is positive for compression, and negative for tension. The axial tensile load reduces the shear strength of the member given it magnifies the impact of cracks on the member strength. It is important to note, for the cases where the tension load is present, the value of V_c shall not be taken less than zero (ACI 318, 2019).

On the other hand, the compressive load helps in improving the shear strength but there is a limit for the effect of axial load in the code. ACI 318-19 limits the value of $N_u/(6A_g)$ to $0.05f_c'$ (ACI 318-19 section 22.5.5.1.2).

2.3.4 Longitudinal Reinforcement Ratio

The area of longitudinal reinforcement, A_s, is another factor that is considered through introducing ρ_w $(= A_s/(b_w d))$ into the ACI 318 OWS strength provisions. The ρ_w is proportional to A_s $(A_s \propto \rho_w)$.

The influence of longitudinal tension reinforcement on the overall shear strength has been changed over time. There is no consensus on if and how to consider the effect of ρ_w in evaluating V_c. In ACI 318-19 provisions, in the simplified method (equation (a) in Table 22.5.5.1) for calculating V_c, the ρ_w is not directly included. However, ρ_w is proportional to $(\rho_w)^{1/3}$ in the detailed approach for calculating V_c as described in ACI 318-19 section 22.5.5 (Equations (b) and (c) in Table 22.5.5.1).

2.3.5 Transverse (Confinement) Reinforcement

The area of the transverse reinforcement, A_{st}, contributes to V_s ($V_s \propto A_{st}$) which helps in improving the overall shear capacity ($\uparrow \mathbf{V_n} = V_c + \uparrow \mathbf{V_s}$).

2.3.6 Transverse Reinforcement Yield Strength

The yield stress of transverse reinforcement, f_{yt}, also contributes to the shear capacity of the member and is proportional to V_s ($V_s \propto f_{yt}$). The actual (measured) yield stress of the reinforcing steel is typically larger than the specified values. Therefore, in this study, to compare the test results with the predicted shear strength more accurately, the measured yield stress of the reinforcing steel is used.

2.3.7 Shear Span Ratio

The shear span ratio (SSR) is defined as $M_u/(V_u\ h)$, where h is the depth of RC column, and V_u is the applied lateral load (shear). M_u is the moment calculated from the applied shear. The M_u/V_u ratio is calculated, using basic statics principles, and is dependent on the boundary condition. The end condition is determined based on the test configuration (more commonly cantilever or double curvature).

2.4 Filters Used

The intent of this research is to evaluate the predicted shear capacity of columns in moment frames under seismic loads, based on ACI 318-19 relationships, and propose the possible changes if required.

The following filters are used to ensure the test results for columns not applicable to this study are excluded:

2.4.1 Shear and Shear-Flexure Failure Modes

The expected failure modes from the test results in laboratory setting can be summarized into the following categories (Abdullah S. A., 2019):

1. Flexure Failure: Bar buckling and concrete core crushing or bar fracture.
2. Shear Failure: Diagonal tension, diagonal compression, or shear sliding at the base (less common).
3. Flexure-Shear Failure: Yielding in flexure and failing in shear.
4. Lap-splice Failure
5. Anchorage Failure
6. Lateral Instability: Global or local lateral instability
7. Not Tested to Failure

For this study, only the shear and flexure-shear failure modes are applicable. Therefore, the specimens with the other failure modes are filtered out.

2.4.2 Columns in Moment Frames Resisting Seismic Loads

Columns are key components of structural systems, and their performance plays a key role in the stability and performance of the structure. There are specific requirements to ensure minimum shear is provided for the members.

This study targets the evaluation of relationships for predicting the shear capacity for RC columns resisting seismic loads. When dealing with lateral cyclic loading such as earthquake, shear resistance of structural members, especially columns, is of a great interest. Having sufficient ductility, mitigates the risk for brittle behavior. In general, a ductile failure is desired as it helps in improving the behavior of structures to tolerate excess loading by the means of energy dissipation mechanisms. In addition, it leads to a more predictable failure form and mitigates the risk for a catastrophic collapse without warning. The shear reinforcement restrains the growth of inclined cracking and helps in improving the ductility of structural members. This is even more crucial when dealing with large tensile loads simultaneously applied with shear which could amplify the risk for larger cracks. In case of having insufficient ductility, the formation of inclined cracking might lead directly to failure without warning. To address this issue, ACI 318 requires minimum shear reinforcement to be provided in all regions where the factored applied shear on the member is greater than 50% of the contribution of concrete to the overall shear resistance of the RC column ($V_u > 0.5\emptyset V_c$). As outlined in ACI 318-19 Chapter 9, the minimum required shear reinforcement is dependent on the concrete compressive strength, f'_c, the width of the column, b_w, the transverse reinforcement spacing, s, and the yield stress, f_{yt}, in general. The minimum shear reinforcement is required to be the greater of (ACI 318, 2019):

(a) $0.75\sqrt{f'_c}^{*} \frac{b_w s}{f_{yt}}$

(b) $50\frac{b_w s}{f_{yt}}$

* The unit of $\sqrt{f'_c(\mathrm{psi})}$ is in psi.

2.5 Selected Specimens

As discussed earlier, a database of column shear test results was created and used in this study. From about 150 specimens, 61 specimens, after applying the filters described in section 2.4, were selected for this study. The test results for these specimens were obtained from applicable publications from 1989 to 2021. The list of these specimens and the reference publication is shown in Appendix A, Table 10.

2.6 Distribution of the Important Parameters in The Filtered Database

The distribution of the key contributing parameters, in the OWS strength of RC columns, is evaluated for the filtered database. This is to ensure a proper range of values is included for the data analysis in this study which is discussed herein:

2.6.1 Distribution of Concrete Compressive Strength

The concrete compressive strength, f_c', for the filtered column database has a reasonable range with a minimum value of 2325.0 psi and a maximum value of 10587.8 psi. The mean value, μ, and the standard deviation, σ, of f_c' are 5419.0 psi and 1942.5 psi, respectively, as shown in Figure 2. In this study the measured concrete compressive strength is used. In cases where the measured value for f_c' is not reported, it is assumed that the specified and measured values are the same.

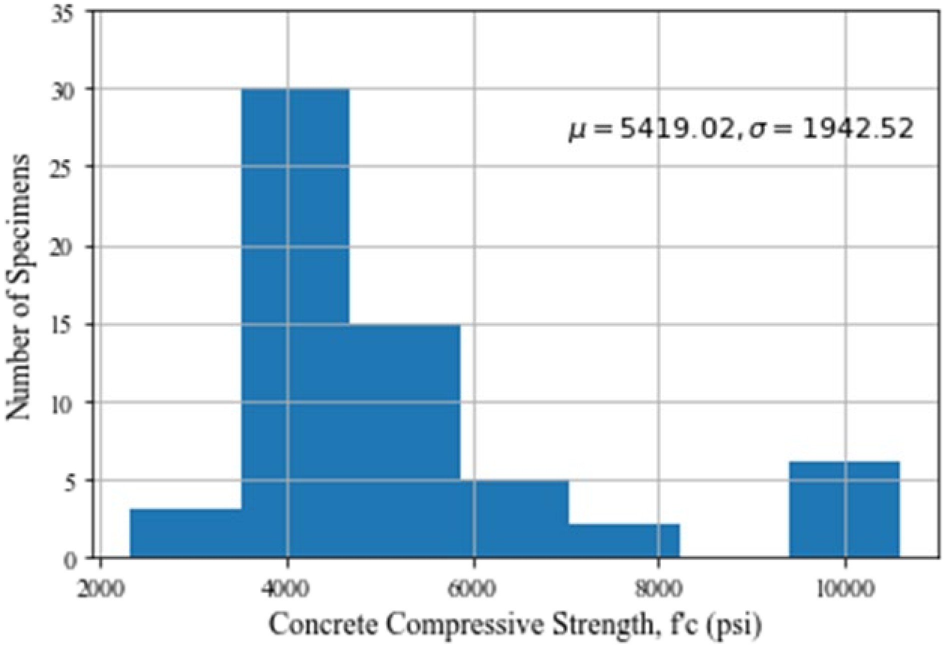

Figure 2: Concrete compressive strength, f'_c, distribution

2.6.2 Distribution of Transverse Reinforcement Yield Strength

The transverse reinforcement yield strength, f_{yt}, for the filtered column database has a reasonable range with a minimum value of 36127.4 psi and a maximum value of 74259.5 psi. The mean value, μ, and the standard deviation, σ, of f_{yt} are 53401.3 psi and 14331.0 psi, respectively, as shown in Figure 3. The same reinforcing steel was used for both, the hoops, and the ties for the specimens used in this study. Also, it is important to note in this project, the measured transverse reinforcing steel strength is used for the analysis. In cases where the measured value for f_{yt} is not reported, it is assumed that the specified and measured values are equal.

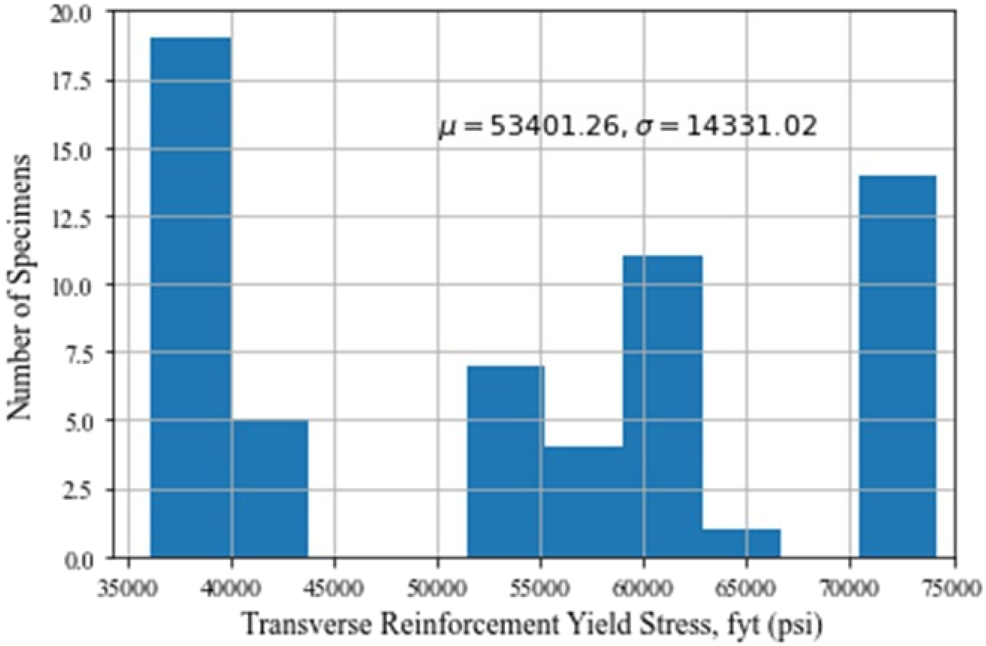

Figure 3: Transverse reinforcement yield strength, f_{yt}, distribution

2.6.3 Distribution of Axial Load Ratio

The axial load ratio (ALR) also has a reasonable range from -7.8% (tension) to +65.2% (compression). The mean value, μ, and the standard deviation, σ, of the axial load ratio are 19.38% and 14.20%, respectively, as shown in Figure 4.

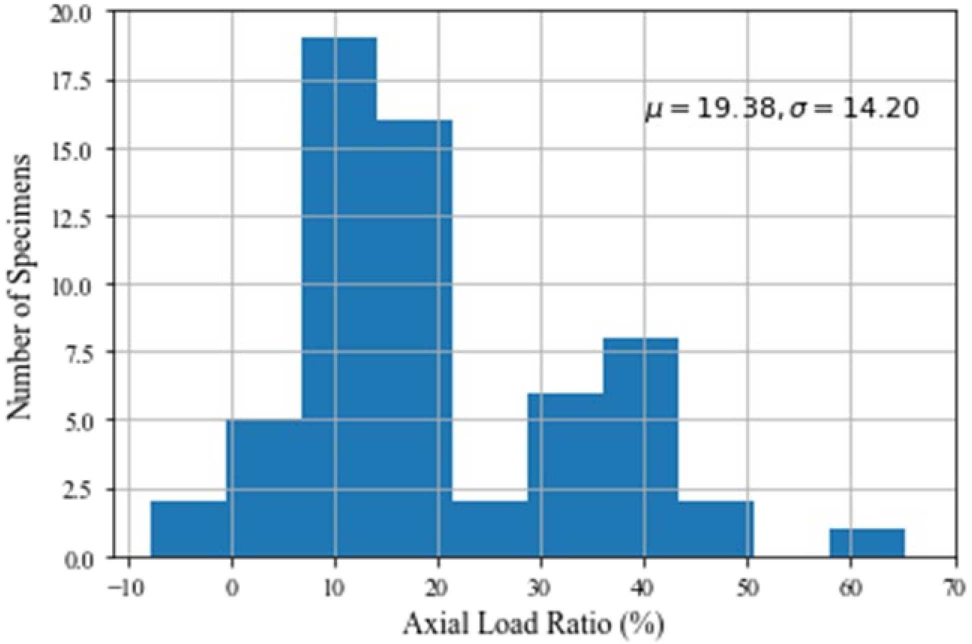

Figure 4: Axial Load Ratio (ALR) distribution

2.6.4 Distribution of Shear Span Ratio

The shear span ratio (SSR) varies from 1.0 to 4.5 with a mean value, μ, of 2.23 and the standard deviation, σ, of 1.14 as shown in Figure 5.

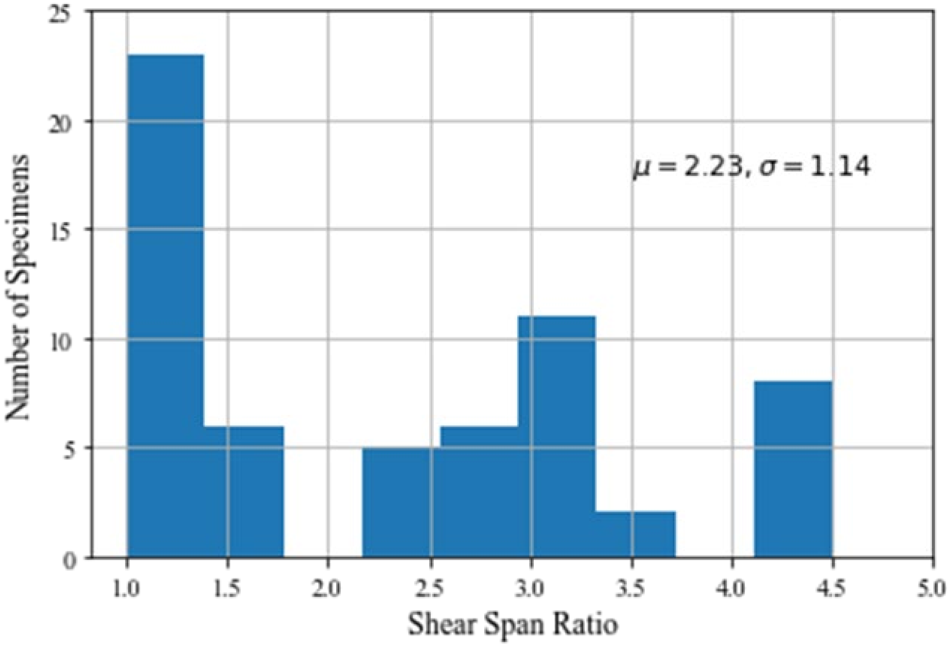

Figure 5: Shear Span Ratio (SSR) distribution

2.6.5 Distribution of Longitudinal Reinforcement Ratio

The longitudinal reinforcement ratio, ρ_w, is reasonably distributed as well, ranging from 1.23% to a maximum value of 4.12%. The mean value, μ, and the standard deviation, σ, of ρ_w are 2.61% and 0.60%, respectively, as shown in Figure 6.

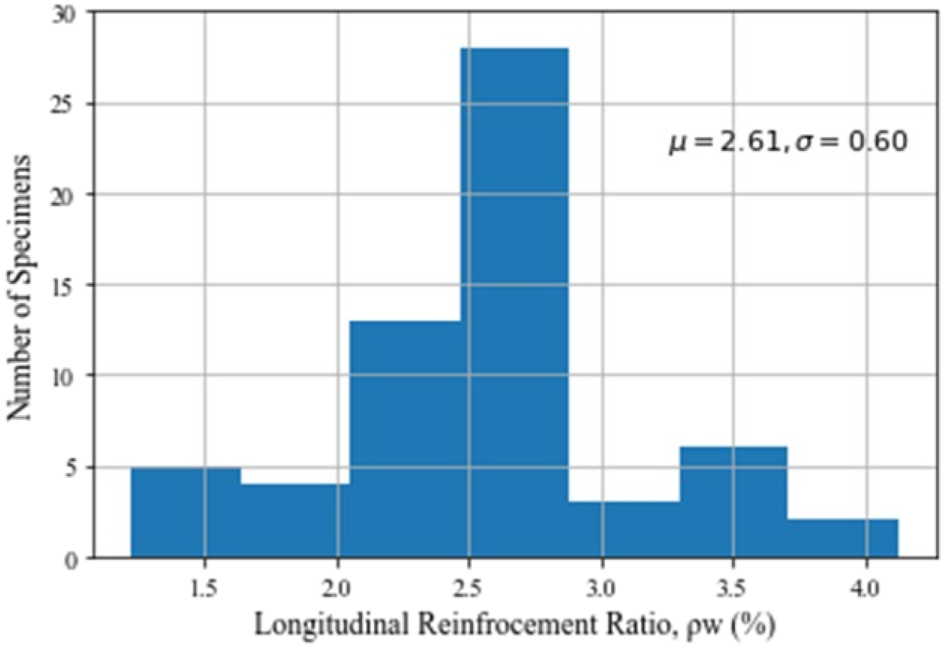

Figure 6: Longitudinal reinforcement ratio, ρ_w, distribution

In the following chapter the current OWS relationships in ACI 318-19 are evaluated and discussed in detail.

Chapter 3: Data Analysis

3.1 General

As discussed in Chapter 2, a column shear database was developed to evaluate the safety and accuracy of the OWS provisions in ACI 318-19 in this project. This database is also intended to be used for further studies on RC columns in the future.

In the first step, the influence of the important parameters, discussed in section 2.2, on reported shear strength from experimental results was evaluated. The following plots were made of the normalized shear strength, $V_{test}/(b_w d\, f_c')$, as a function of the important parameters, discussed in section 2.6, to assess trends and thereby better understand their influence on the overall shear capacity.

No specific trend in shear strength with respect to f_c' or f_{yt} was observed as shown in Figures 7 and 8, respectively. However, it was observed that there is an increasing trend in the shear strength when the ρ_w is less than about 2.5% (which is applicable to the majority of the specimens in the database) as depicted in Figure 9.

Moreover, it was observed that the shear capacity has an increasing trend with respect to the axial compressive stress expressed as ALR shown in Figure 10.

In Figure 11, the influence of SSR on the recorded shear strength is shown. The ACI 318-19 methods do not consider the impact of SSR. The results suggest that there is a decreasing trend in the recorded shear strength as the SSR increases, particularly when the SSR is larger than 2.0.

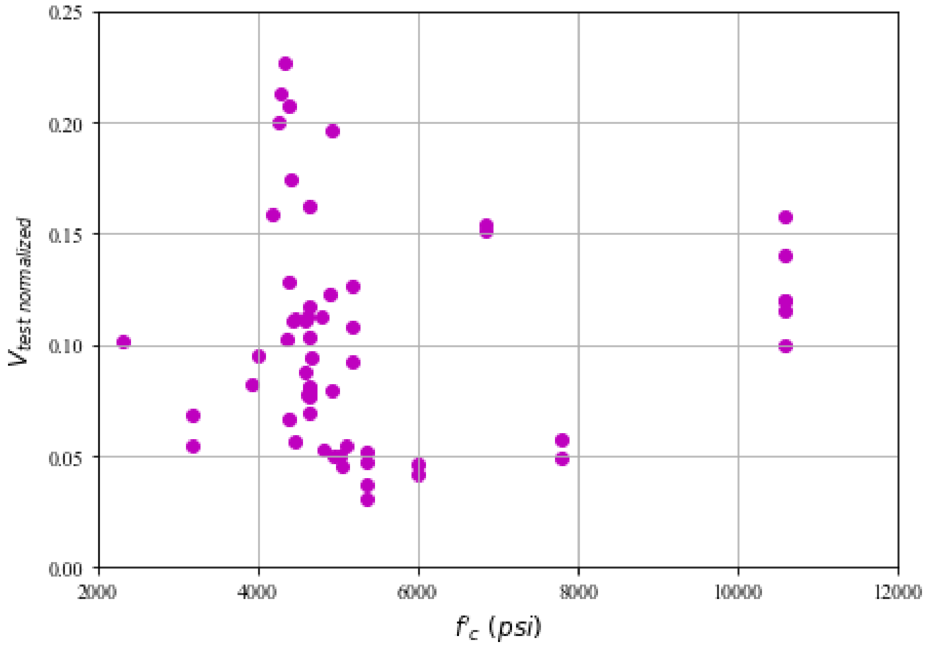

Figure 7: Influence of f'_c on recorded RC column shear strength

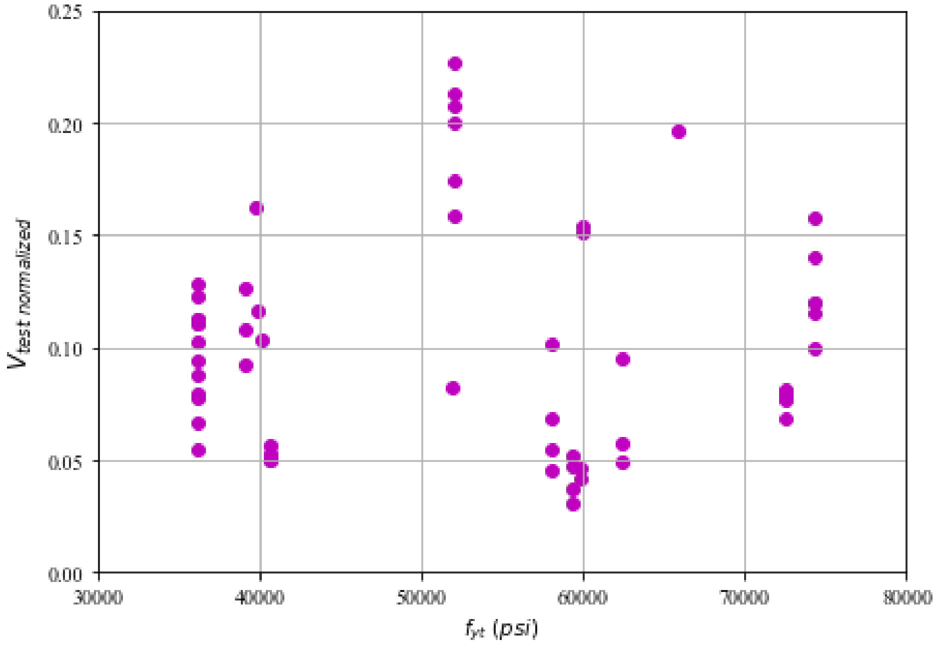

Figure 8: Influence of f_{yt} on recorded RC column shear strength

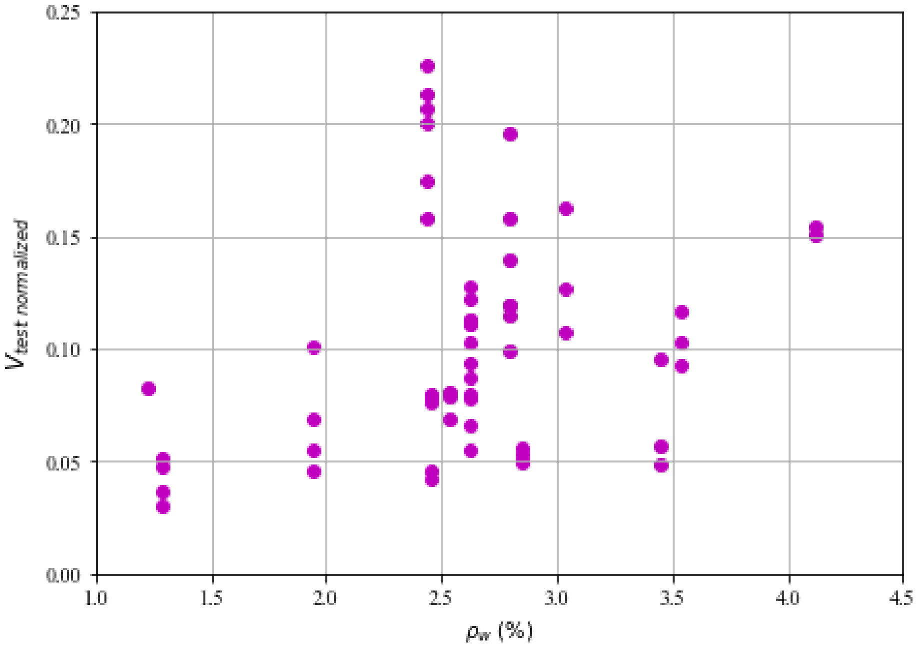

Figure 9: Influence of ρ_w on recorded RC column shear strength

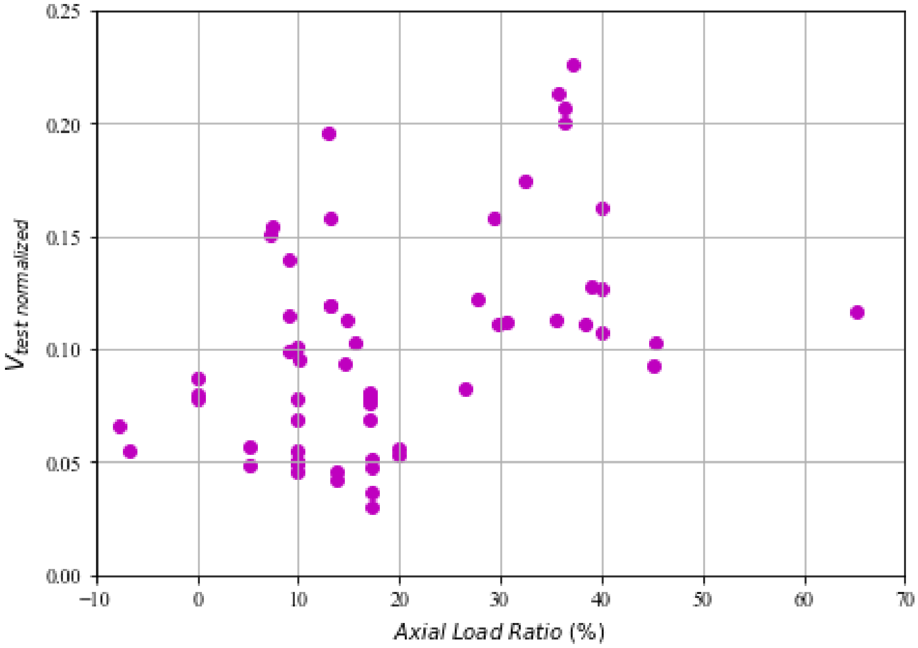

Figure 10: Influence of ALR on recorded RC column shear strength

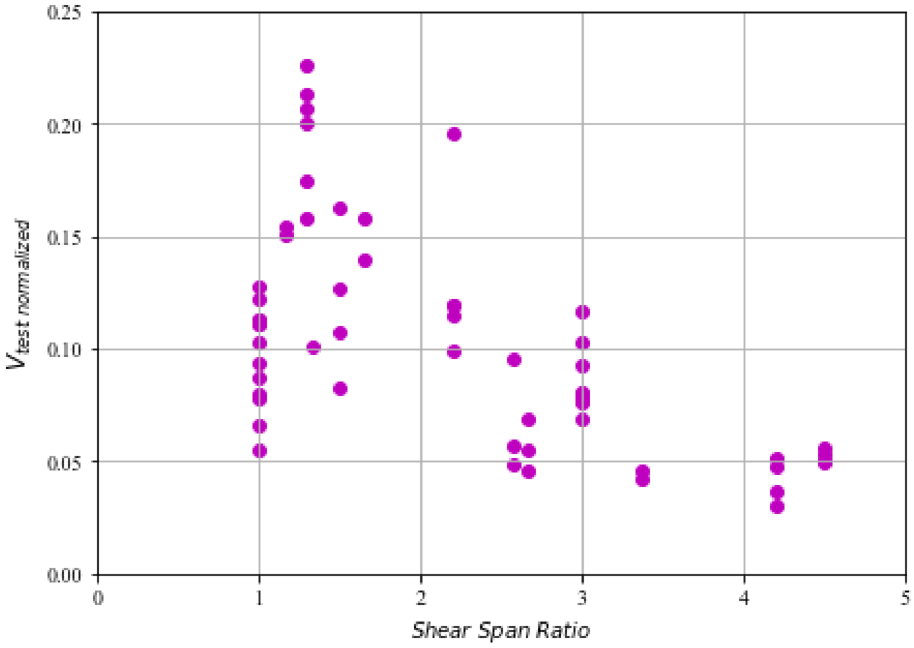

Figure 11: Influence of SSR on recorded RC column shear strength

In the following section, a more detailed analysis is done by comparing the shear capacity of RC columns from the database to the estimated shear strength using the ACI 318-19 OWS provisions to evaluate the comparative accuracy and safety of these relationships.

3.2 Comparative Accuracy and Safety of ACI 318-19 Shear Strength Relationships

The results from the column database are used to calculate the ratio of column shear capacity and the calculated shear strength using the ACI 318-19 OWS provisions. The SR is plotted as a function of the key parameters contributing to the OWS shear strength such as f_c', f_{yt} , AAR, and SSR to evaluate the trends and assess the influence of these parameters in the OWS relationships.

For a comparative evaluation of these relationships, the following statistical parameters are utilized:

1. Root Mean Square Error (RMSE): The RMSE is a frequently used method to measure the error for numerical predictions (Jack R. Benjamin, 2014). RMSE is defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}(\sum_{i=1}^{n} (\mathrm{Prediction}_i - \mathrm{Observation}_i)^2}$$

$*$ n is the number of observations for the analysis

2. R-Squared (R^2): The R^2, which is commonly referred to as the determination coefficient, is a statistical measure generally used in linear regression models to evaluate how well the data fits the model (Jack R. Benjamin, 2014). The formula for R^2 is:

$$R^2 = 1 - \frac{\text{residuals sum of squares}}{\text{total sum of squares}} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{Observation}_i - \mathrm{Prediction}_i)^2}{\sum_{i=1}^{n}(\mathrm{Observation}_i - \text{Mean of Observations})^2}$$

$*$ n is the number of observations for the analysis

3. Coefficient of Variation (CV): CV is the ratio of the standard deviation to the mean. It is a ratio commonly used in the data analysis which shows the extent of variability in relation to the mean of the population (Jack R. Benjamin, 2014). Typically, for similar studies, a maximum value of 0.30 is targeted for CV to minimize the dispersion.

3.2.1 Evaluation of ACI 318-19 OWS Equation (a)

In ACI 318-19 section 22.5.5, equation (a) is presented as a simplified approach for calculating OWS. This relationship is a simplified form of equation (b), which predicts the concrete contribution to the shear strength, V_c, without including ρ_w as shown below:

$$V_c = [2\lambda\sqrt{f_c'} + \frac{N_u}{6\,A_g}]\, b_w d$$

To compare the column shear strength, from the test results, to the nominal shear capacity (V_n) using equation (a), the mean value, μ, the standard deviation, σ, and the coefficient of variant, CV, for SR are calculated. The SR has a mean value of 1.26, a relatively large CV of 0.50 and relatively low accuracy as it can be interpreted from the R^2 which is about 0.35. To better illustrate the performance of the ACI 318-19 equation (a), the SR is plotted as a function of the normalized measured shear strength ($V_{test}/(f_c' b_w d)$) in Figure 12. As depicted in this figure, the majority of the SRs are greater than 1.0 and are dispersed, particularly when the normalized measured shear strength is larger than 0.10.

In summary, from evaluating the above-mentioned statistical parameters, and Figure 12, it can be concluded that this method considerably underpredicts the actual shear capacity and has a relatively large error, thus requires further improvement.

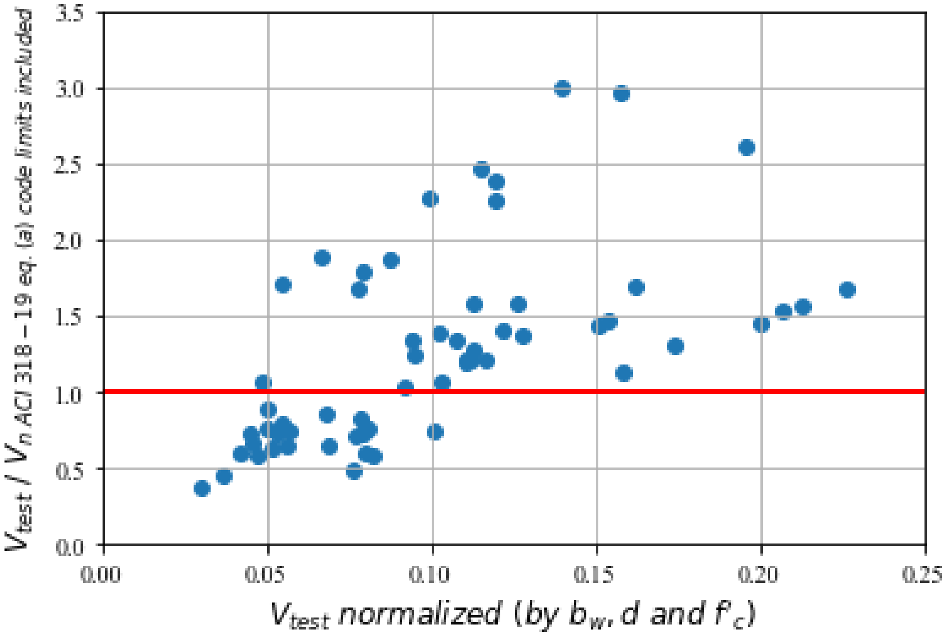

Figure 12: V_{test}/ ($b_w d f'_c$) *vs SR using ACI 318-19 eq. (a)*

To examine trends in SR and possible bias towards important parameters, the SR values are plotted as a function of the important parameters, and are discussed in the following section:

3.2.1.1 Influence of Important Parameters on The Predicted OWS Strength Using ACI 318-19 Equation (a):

The impact of important parameters including f'_c, f_{yt}, ρ_w, ALR and SSR on equation (a) for predicting the OWS strength are evaluated and discussed in this section.

As it can be interpreted from Figures 13 and 14, there is no specific trend in SR with respect to f'_c or f_{yt}, respectively. The same steel grade was used for hoops and ties in the specimens considered in this study. Therefore, the hoops and ties in this study have the same f_{yt}.

The results presented in Figure 15 show that the predicted shear strength using equation (a) is significantly lower than the expected shear strength, obtained from the test results, for columns having ρ_w more than about 2.5%.

Examining the impact of ALR, as depicted in Figure 16, indicates that the predicted shear strength based on equation (a) is significantly lower than the shear strength from test results, for a majority of the specimens. The predicted shear strength appears to be more conservative for members having ALR less than about 10%, and also for members under tension. However, due to limited data available for members in tension, more experimental data would be required to investigate the accuracy of the OWS provisions for RC columns under tension loads.

Similarly, the impact of SPR on the predicted OWS is examined. As depicted in Figure 17, the results suggest that equation (a) underpredicts the OWS strength for the columns with the SSR less than about 2.0. In general, for members with smaller SSRs, the shear capacity is expected to be larger, and this is aligned with the test results.

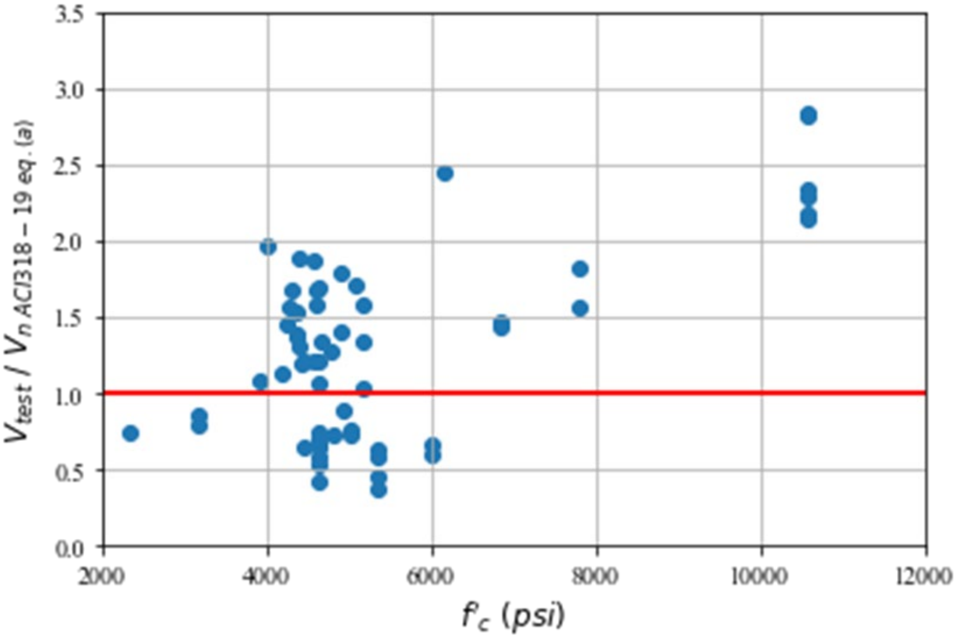

Figure 13: Influence of f'_c on V_n using ACI 318-19 Eq. (a)

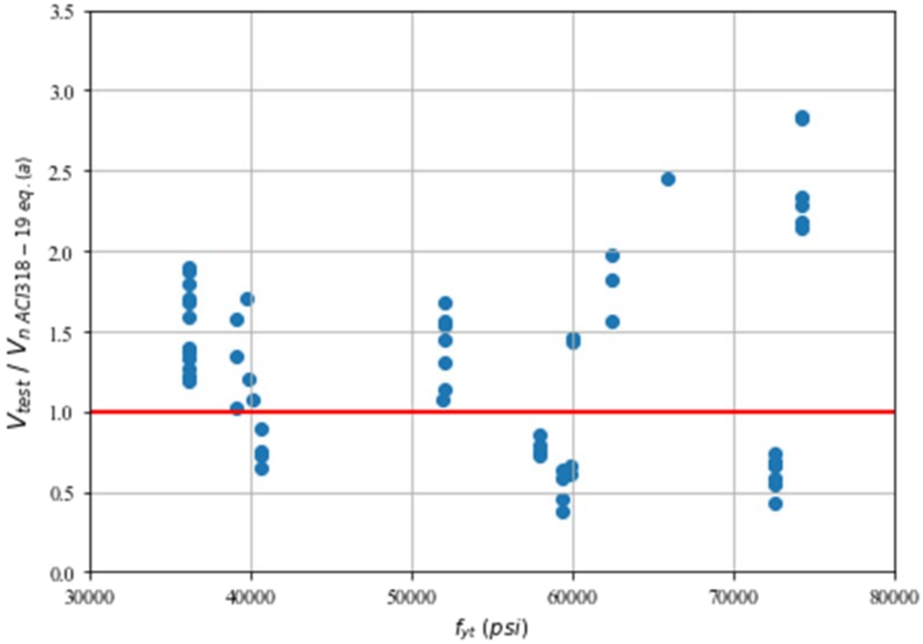

Figure 14: Influence of f_{yt} on V_n using ACI 318-19 Eq. (a)

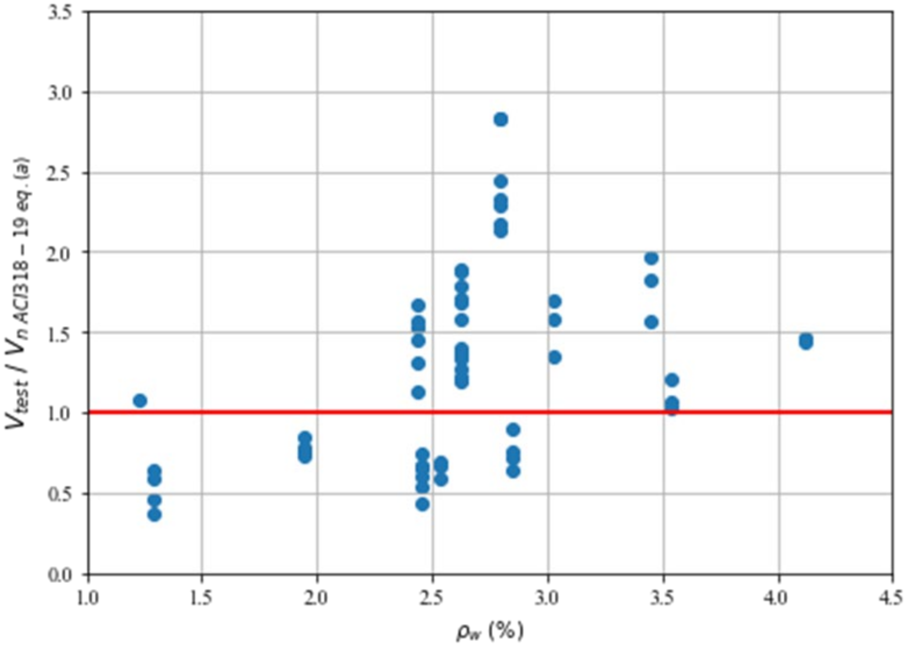

Figure 15: Influence of ρ_w on V_n using ACI 318-19 Eq. (a)

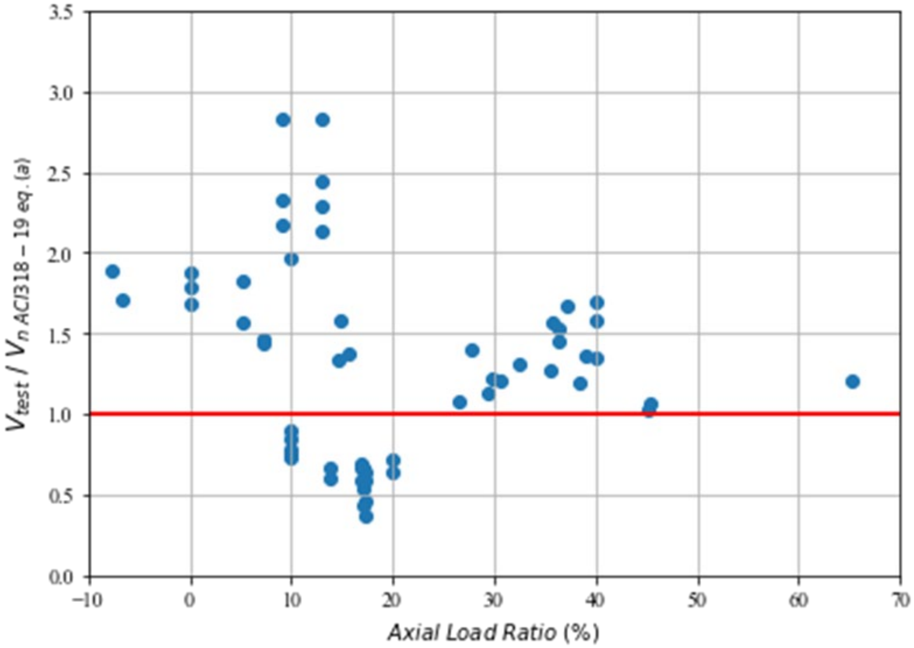

Figure 16: Influence of Axial Load Ratio on V_n using ACI 318-19 Eq. (a)

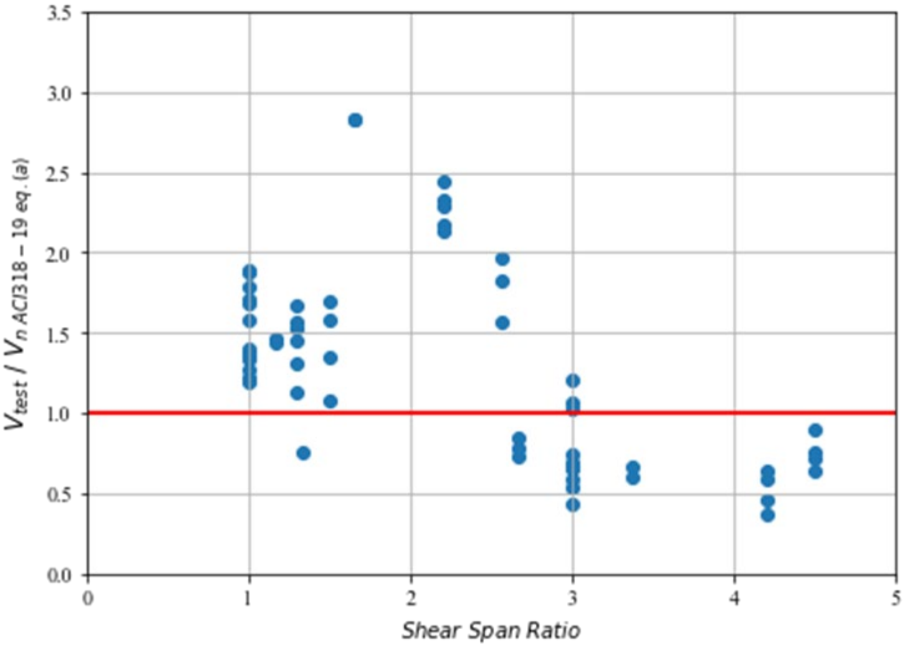

Figure 17: Influence of Shear Span Ratio on V_n using ACI 318-19 Eq. (a)

3.2.2 Evaluation of ACI 318-19 OWS Equation (b)

When $A_v \geq A_{v,min}$, which is applicable to this study, ACI 318-19 does not include the size effect factor, λ_s, in the OWS relationships. In this case, the code introduces equation (b) in section 22.5.5 as a more detailed approach for predicting the concrete contribution to the shear strength, V_c, with including ρ_w as shown below:

$$\left[8\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6\,A_g}\right]b_w d$$

Similar to the approach taken previously in section 3.2.1, to compare the column shear strength, from the test results, to the nominal shear capacity (V_n) using equation (b), the mean value, μ, the standard deviation, σ, and the coefficient of variant, CV, for the SRs are calculated. The mean value of SR is 1.20, which is about 5% lower than the SR mean value based on equation (a). However, it still considerably underpredicts the shear strength. The CV and the R^2 which are 0.48, and 0.34, respectively, are relatively close to the CV and R^2 of SR using equation (a). Therefore, it can be concluded that equation (b) performs slightly better than equation (a) as expected. However, the improvement to the accuracy of the predicted strength is not considerable. As depicted in Figure 18, the majority of the SRs even for the detailed method are greater than 1.0 and are dispersed, particularly when the normalized measured shear strength is larger than 0.10.

In light of this information and also as presented in Figure 18, it can be interpreted that equation (b) is slightly less conservative from equation (a). Nonetheless, it still has a considerable error and requires further improvement.

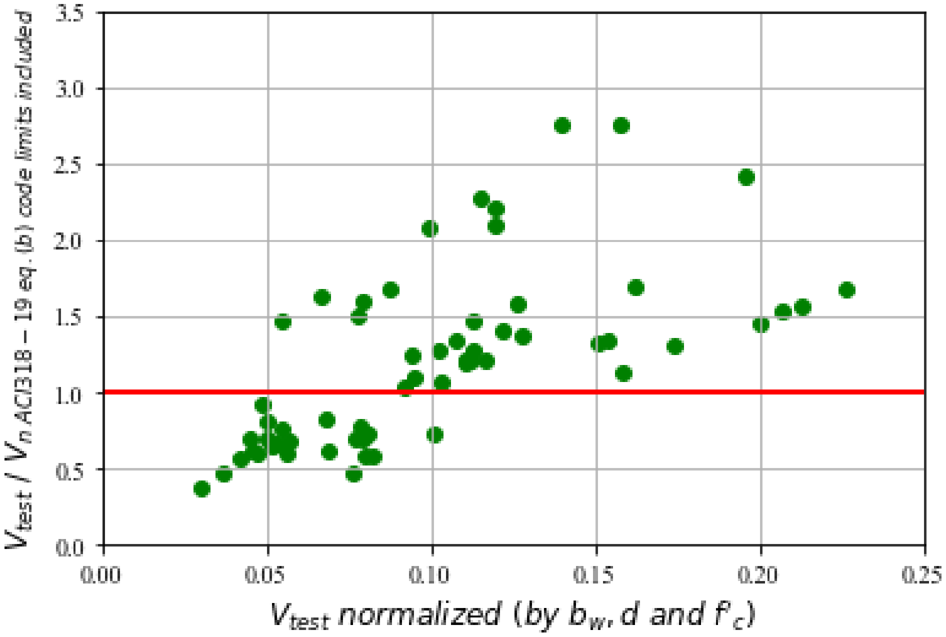

Figure 18: V_{test}/ ($b_w d f'_c$) vs SR using ACI 318-19 eq. (b)

3.2.2.1 Influence of Important Parameters on The Predicted OWS Strength Using ACI 318-19 Equation (b):

Similar to the procedure followed for evaluating the performance of equation (a), and the impact from the important parameters in the section 3.2.1.1, the influence of f'_c, f_{yt}, ρ_w, ALR and SSR on equation (b) for predicting the OWS strength have been evaluated in this section. As it can be interpreted from Figures 19 and 20, there is no specific trend in SR with respect to f'_c or f_{yt}, respectively.

The results presented in Figure 21 indicate that the predicted shear strength using equation (b) is also significantly lower than the expected shear strength, obtained from the test results, for members having ρ_w more than about 2.5%. However, the impact of ρ_w is more prominent in the predicted OWS strength based on equation (a) as expected. This trend is slightly less in equation (b) compared to equation (a), as expected, given the detailed method directly includes ρ_w in the equation, making it proportional to $(\rho_w)^{1/3}$. However, the impact of ρ_w when the value is more than about 2.5% is underestimated consistently as depicted in Figure 21.

Examining the impact of ALR on the predicted shear strength based on equation (b), as depicted in Figure 22, suggest that this equation also significantly underpredicts the shear strength from test results, more consistently for members with ALR more than about 30%.

The impact of SSR on the predicted OWS strength for both cases were relatively similar. As depicted in Figure 23, the results show that equation (b) also underpredicts the OWS strength for columns with the SSR less than about 2.0.

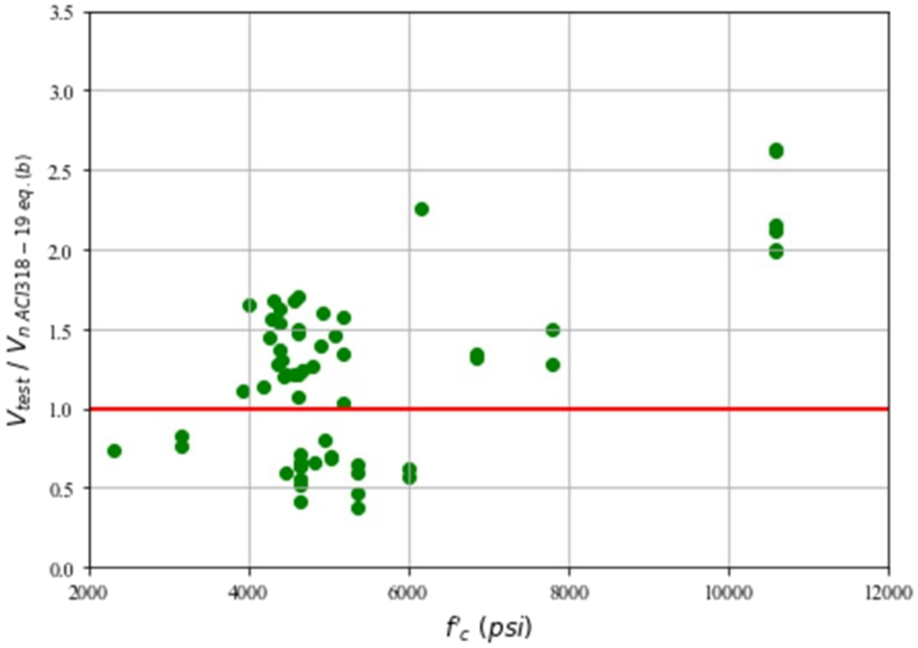

Figure 19: Influence of f'_c on V_n using ACI 318-19 Eq. (b)

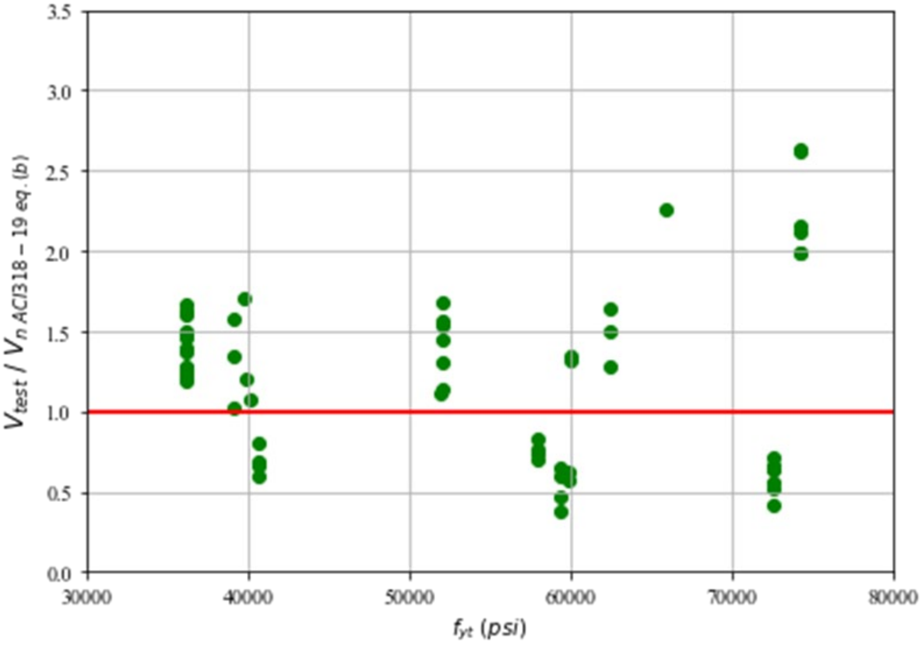

Figure 20:Influence of f_{yt} on V_n using ACI 318-19 Eq. (b)

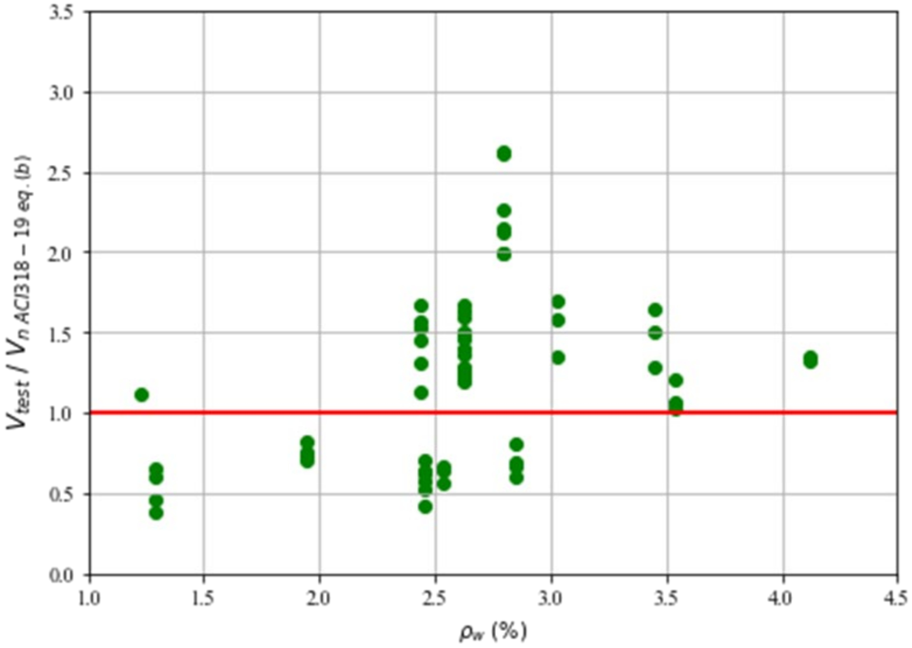

Figure 21: Influence of ρ_w on V_n using ACI 318-19 Eq. (b)

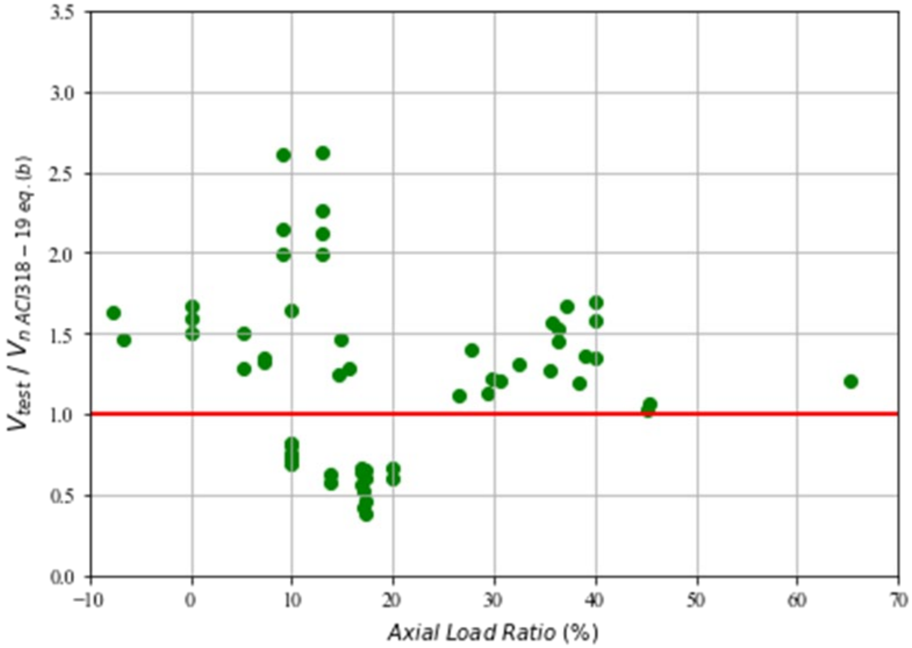

Figure 22: Influence of Axial Load Ratio on V_n using ACI 318-19 Eq. (b)

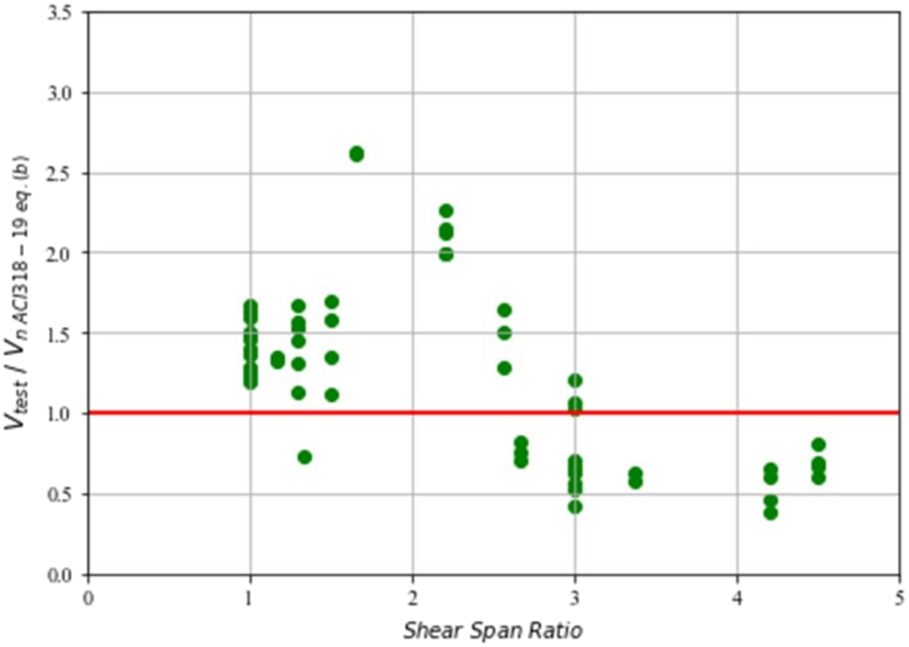

Figure 23: Influence of Shear Span Ratio on V_n using ACI 318-19 Eq. (b)

3.2.3 Comparison Between ACI 318-19 OWS Equations (a) and (b)

The evaluation of the ACI 318-19 OWS relationships using the column database, shows that the performance of the detailed approach overall is slightly better than the performance of the simplified method, as expected, given it directly considers the effect of longitudinal reinforcement on the concrete contribution (V_c) to the column OWS strength ($V_n = V_c + V_s$) but the difference is not considerable from the data analysis. As it can be interpreted from Table 3, further improvement to the current relationships in ACI 318-19 is required to be investigated.

Table 3: Comparative evaluation of ACI 318-19 relationships (code limits included)

Method	**SSR Considered (Yes/ No)**	**With Code Limits**			
		Mean	**CV**	**R^2**	**RMSE**
ACI 318-19 Simplified	**No**	1.26	0.50	0.35	0.0465
ACI 318-19 Detailed	**No**	1.20	0.48	0.34	0.0456

The equation (a) and equation (b), both, significantly underestimate the OWS strength, especially for columns with higher ALR as depicted above. Moreover, the test results, suggest that the impact of ρ_w on improving the OWS strength has been underestimated for columns with ρ_w more than about 2.5%.

The results also indicate that, the impact of axial load on OWS strength, especially, when the ALR is more than about 30% is considerably underpredicted.

Moreover, the impact of SSR is not considered in the ACI 318-19 OWS provisions for RC members. As depicted in Figures 11, 17 and 23, there is an inclination in the column shear capacity as the SSR increases which needs to be investigated further.

In the following chapter, the possible improvements to the ACI 318-19 OWS relationships are discussed.

Chapter 4: Evaluation of ACI 318-19 Shear Strength Relationships for RC Columns and Proposed Changes

4.1 General

In Chapter 3, the safety and accuracy of the ACI 318-19 OWS provisions for RC columns were evaluated. It was concluded that the existing relationships, significantly underpredict the OWS strength for RC columns having ρ_w more than about 2.5% and also RC columns with large axial loads. In addition, it was concluded that the SSR is an important parameter which considerably influences the shear capacity. However, it is not directly included in the ACI 318-19 OWS provisions. As discussed in Chapter 3, considering the SSR in the OWS provisions is expected to help in improving the predicted shear strength, especially for columns with SSR less than about 2.0.

In this section, the possible changes to the ACI 318-19 OWS relationships for RC columns for improving the predicted values are discussed:

4.2 General Form of ACI 318-19 Shear Strength Relationships

The OWS strength of a structural member is composed of the contributions from the RC concrete (V_c) and the transverse reinforcement (V_s) as discussed earlier. The relationships developed for calculating the OWS contain some empirical coefficients, mostly drawn through regression analysis of test data obtained from experiments performed on RC members.

The relationships in ACI 318-14 for calculating the concrete contribution to OWS resistance in non-prestressed RC members were replaced by a general relationship in ACI 318-19 which has the following general form:

$$V_n = V_c + \boldsymbol{\alpha_3} V_s$$

$$\left[\boldsymbol{\alpha_1}\lambda(\rho_w)^{\mathbf{b_1}} f_c'^{\mathbf{b_2}} + \boldsymbol{\alpha_2}\frac{N_u}{A_g}\right] b_w d$$

$$V_s = A_v f_{yt}\frac{d}{s}$$

As discussed earlier, there are two general approaches for calculating the OWS strength in ACI 318-19, the simplified method, equation (a), and the detailed method, equations (b) or (c), introduced in section 22.5.5.1. Equation (c) is similar to equation (b) with the addition of the size effect factor (λ_s). Equation (c) is for RC members not meeting the minimum transverse reinforcement requirement which does not apply to this study as discussed.

The value of the defined variables (α and b) for the general form in ACI 318-19 are summarized below:

- For calculating V_n based on equation (a):
  - ➢ $\alpha_1 = 2.0$
  - ➢ $\alpha_2 = 1/6$
  - ➢ $\alpha_3 = 1.0$
  - ➢ $b_1 = 0$
  - ➢ $b_2 = 1/2$
- For calculating V_n based on equation (b):
  - ➢ $\alpha_1 = 8.0$
  - ➢ $\alpha_2 = 1/6$
  - ➢ $\alpha_3 = 1.0$
  - ➢ $b_1 = 1/3$
  - ➢ $b_2 = 1/2$

The 100% contribution from V_s is commonly considered ($\alpha_3 = 1.0$) in the ACI 318 provisions. However, in this study this contribution has been evaluated for RC columns with the conditions discussed in section 2.4, along with the other scalars (α_1 and α_2) and the power of ρ_w (b_1) and f'_c (b_2). Moreover, the possible influence of SSR on the OWS strength was studied which is discussed in detail herein.

4.3 Process Used in Evaluation and Optimization of The OWS Provisions

In the evaluation and selection process of the new OWS relationship for RC columns, the following considerations were given particular attention:

1. Influence of axial load
2. Influence of longitudinal reinforcement (ρ_w)
3. Influence of shear span ratio
4. The existing upper limit on $\sqrt{f'_c}$ (outlined in ACI 318-19 section 22.5.3.1)
5. The existing upper limits on f_y and f_{yt} (outlined in ACI 318-19 section 22.5.3.3)
6. The existing upper limit on V_c (outlined in ACI 318-19 section 22.5.5.1.1)
7. The existing upper limit on the axial load term in the OWS relationships (outlined in ACI 318-19 section 22.5.5.1.2)
8. The contribution of V_s (by defining the α_3 scalar as discussed in section 4.2).

The relationships were evaluated by running several regression models in an attempt to improve the accuracy of the predicted values without compromising the ease of use as far as possible. The optimization process was step by step, starting from simple, evaluating the performance based on the new changes and adding more complexity as required to obtain a reasonable result. The evaluation and selection of the coefficients were based on balancing precision, ease of use while minimizing the changes where possible.

4.4 Regression Analysis and Optimization of The OWS Provisions

In this study the accuracy and safety of the existing shear provisions in ACI 318-19 were examined by comparing the measured shear strength of RC columns, using the developed column database, to the calculated shear strength using the ACI 318-19 relationships. The SR values were plotted as a function of the important parameters such as ρ_w, f'_c, ALR and SSR, to evaluate the trends and assess the influence of these parameters on the predicted OWS strength as discussed in detail in section 3.2.

The evaluation and selection of the coefficients were based on balancing accuracy, ease of use with an attempt to minimize the changes as discussed earlier. In the initial regression analysis, for the evaluation of the SRs, no limitations were considered for f'_c, f_{yt}, or V_s, even if these values were limited per the ACI 318 upper bounds, to have a more accurate evaluation. If the limits were considered, the SR values would be higher than the realistic values (more conservative). However, after identifying the required changes, the ACI 318-19 limits were examined for possible updates to obtain more accurate relationships.

The intent was to improve the accuracy of the OWS relationships, without compromising the acceptable safety. The target was to lower the mean value to about 1.0, while limiting the coefficient of variation (CV) to a maximum value of 0.30 and minimizing the error by comparative evaluation of RMSE and R^2.

The initial regression analysis was done in the following five general steps which are discussed herein:

- Step 1: Optimization Based on α_1, and α_2
- Step 2: Optimization Based on α_1, α_2 and b_1
- Step 3: Optimization Based on α_1, α_2 and b_1 and b_2
- Step 4: Optimization Based on α_1, α_2, α_3 and b_1
- Step 5: Optimization Based on α_1, α_2, α_3, b_1 and b_2

The first regression analysis was based on just scalar 1 (α_1) and scalar 2 (α_2). The results showed that by updating these scalars, the mean value can be considerably improved. However, the target accuracy was not achievable. Therefore, in step 2, the power of ρ_w (b_1) was included in the regression analysis. This helped in improving the CV slightly but not to the acceptable level. In step 3, varying the power of f_c' (b_2), in addition to the previous parameters, was examined. Similarly, the improvement to the CV was not satisfactory.

Next, the contribution from the transverse reinforcement was evaluated by including α_1, α_2, α_3 and b_1, and also by applying a reduction factor (α_3) to V_s (step 4), and eventually including b_2 as well (step 5). The inclusion of the reduction factor had a noticeable influence on improving the accuracy of the predicted shear strength. It was observed that for the lowest CVs, the reduction factor was in the range of 0.6 to about 0.8. However, even in the best case, the value of CV was still about 0.35. The possible improvement by introducing a power for axial load ratio was also investigated which didn't seem to be helpful.

Subsequently, the possible influence of SSR on the predicted OWS capacity for RC concrete columns was investigated. The data from the column test results, as depicted in Figures 17 and 23, shows that when the SSR is less than about 2.0, the ACI 318-19 OWS relationships underpredict the maximum resisted shear from the experimental data. Therefore, using different values for α_1, depending on the SSR, was considered. A larger scalar value (α_1) when the SSR is less than 2.0 and a smaller scalar value when the SSR is larger than about 3.0, based on the results from the column database as shown in Figures 11, 17 and 23. This helped in improving the predicted values considerably.

The initial regression analysis, as discussed above, helped in better understanding of the influence from different parameters on predicted OWS strength using ACI 318-19 provisions. It was concluded that including the SSR, particularly, and applying the reduction factor on V_s can possibly help in improving the accuracy of the OWS relationships which is discussed, in detail, herein.

4.4.1 Comparative Evaluation of ACI 318-19 OWS Relationships (Code Limits for ALR and $V_{c,\,max}$ Excluded)

For a comparative evaluation of the ACI 318-19 relationships, the data from the RC column database was used to compute the statistical parameters similar to the approach taken in section 3.2.3. This time in order to have a more accurate evaluation, the code limits, including the upper bounds for $V_{c,\,max}$ and the axial load term outlined in ACI 318-19 sections 22.5.5.1.1 and 22.5.5.1.2, were not considered. As shown in Table 4, the mean value for the detailed approach is about 7% lower than the mean value for the simplified approach. However, the CV for both cases is close to 0.5, and the R^2 is about 0.4. From the evaluation of the statistical values, summarized in Table 4, and the plots shown in Figure 24, it can be concluded that the dispersion is notable and the accuracy of the ACI 318-19 OWS provisions require further improvement.

Table 4: Comparative evaluation of ACI 318-19 relationships (code limits excluded)

Method	**SSR Considered (Yes/ No)**	**Without Code Limits**			
		Mean	**CV**	**R^2**	**RMSE**
ACI 318-19 Simplified	**No**	1.20	0.52	0.37	0.0441
ACI 318-19 Detailed	**No**	1.12	0.50	0.36	0.0427

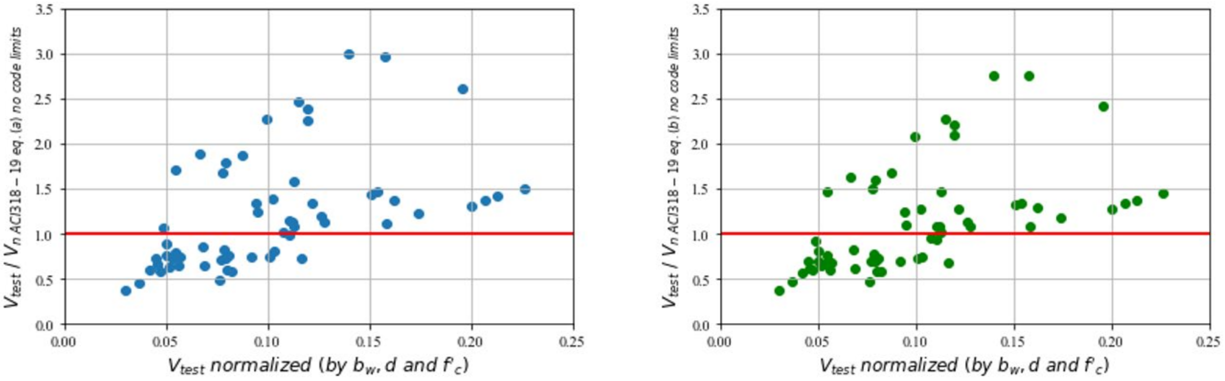

Figure 24: Comparative Evaluation of ACI 318-19 Relationships (Code Limits Excluded)

Figure 24(a): ACI 318-19 Equation (a) (figure on the left)

Figure 24(b): ACI 318-19 Equation (b) (figure on the right)

In attempt to come up with a more accurate relationship for predicting the OWS strength for RC column, the regression analysis was done based on α_1, α_2, α_3, b_1 and b_2 and the SSR, and the coefficients were selected accordingly.

The evaluation of SSR which appeared to have a considerable influence on improving the OWS provisions is discussed first in section 4.4.2, and then the influence of α_3 is examined in section 4.4.3.

4.4.2 Influence of SSR on Revised Relationships (Code Limits for ALR and $V_{c,\,max}$ Excluded)

As discussed earlier, the results obtained from the analysis of the column database, indicated that the SSR was one of the parameters influencing the OWS strength. However, it was not directly considered in the ACI 318 OWS provisions for RC members.

After the initial regression analysis, which was discussed in the previous section, the following forms of the OWS relationships were selected (refer to section 4.2 for the general parametric form of the equation):

- SSR considered:
  - $\alpha_1 = 2.0$
  - $\alpha_2 = 1/6$
  - $\alpha_3 = 1.0$
  - $b_1 = 1.25$
  - $b_2 = 1.0$

- SSR not considered:
  - $\alpha_1 = \begin{cases} 5.5 & \text{for } \mathrm{SSR} \leq 2.0 \\ \text{linear interpolation} & \text{for } 2.0 < \mathrm{SSR} < 3.0 \\ 1.5 & \text{for } \mathrm{SSR} \geq 3.0 \end{cases}$
  - $\alpha_2 = 1/6$
  - $\alpha_3 = 1.0$
  - $b_1 = 1.25$
  - $b_2 = 1.0$

Similar to the approach taken in the previous section, the statistical parameters for the two cases are calculated and presented in Table 5.

As shown in Table 5, considering the SSR helped in reducing the CV from 0.41 to 0.28 (close to 32% improvement), and increasing the R^2 from 0.30 to 0.50 (close to 67% improvement). This indicates that including the SSR has a considerable impact on minimizing the dispersion and improving the accuracy of the predicted OWS strength for RC columns. A comparison between the plots shown in Figures 25(a) and 25(b) confirms the improvement to the precited OWS strength as well.

Table 5: Influence of SSR on revised OWS relationships (code limits excluded)

Method	**SSR Considered (Yes/ No)**	**Without Code Limits**			
		Mean	**CV**	**R^2**	**RMSE**
New **$\alpha_3 = 1$**	**No**	0.98	0.41	0.30	0.04202
New **$\alpha_3 = 1$**	**Yes**	0.96	0.28	0.50	0.0287

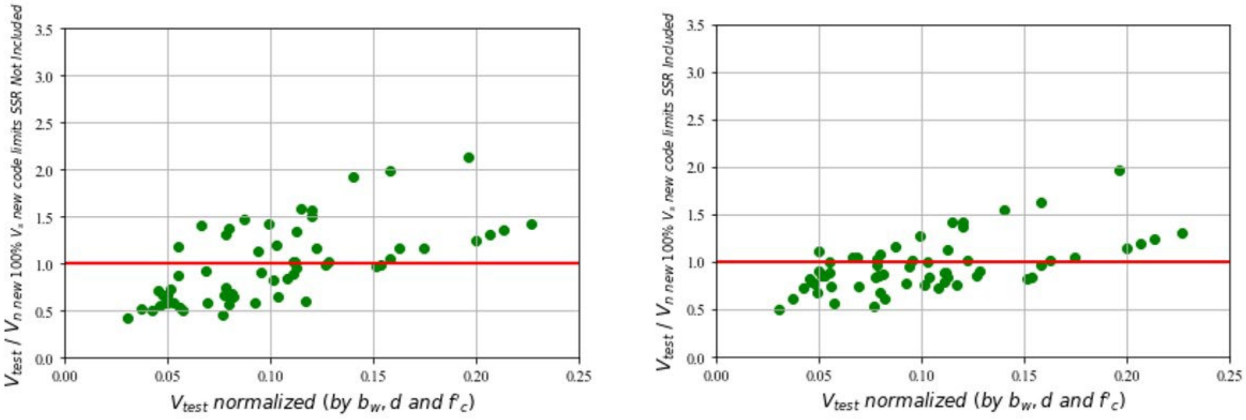

Figure 25: Influence of SSR on Revised OWS Relationships (Code Limits Excluded)

Figure 25(a): SSR Not Included (figure on the left)

Figure 25(b): SSR Included (figure on the right)

4.4.3 Influence of Transverse Reinforcement Contribution (α_3) on Revised Relationships (Code Limits for ALR and $V_{c,\max}$ Excluded)

Another parameter which appeared to be effective in improving the accuracy of the predicted OWS strength is the V_s reduction factor (α_3).

As it was concluded in the previous section, the SSR had a considerable influence on improving the predicted shear strength. Therefore, the proposed relationship, with the SSR considered, is used for examining the influence of α_3 on improving the predicted shear strength.

Based on the results obtained from the regression analysis, and the considerations discussed for selection of the coefficients, the proposed OWS relationship (with the SSR included) is evaluated for the following two cases. The first case, using 100% contribution ($\alpha_3 = 1$), and the second case with considering 75% contribution ($\alpha_3 = 0.75$) from V_s.

Similarly, the statistical parameters for the above-mentioned cases are calculated and shown in Table 6. As it can be concluded from the computed statistical parameters, and also Figures 26(a) and 26(b), the reduction factor on V_s does not make a considerable difference on the mean or CV. However, it increases the R^2 from 0.50 to about 0.73, meaning it improves the accuracy by about 46% (based on running the analysis on the experimental results shown in Appendix A, Table 10).

Table 6: Influence of V_s contribution (α_3) on revised OWS relationships (code limits excluded)

Method	**SSR Considered (Yes/ No)**	**Without Code Limits**			
		Mean	**CV**	**R^2**	**RMSE**
New **$\alpha_3 = 1$**	**Yes**	0.96	0.28	0.50	0.0287
New **$\alpha_3 = 0.75$**	**Yes**	1.04	0.27	0.73	0.0276

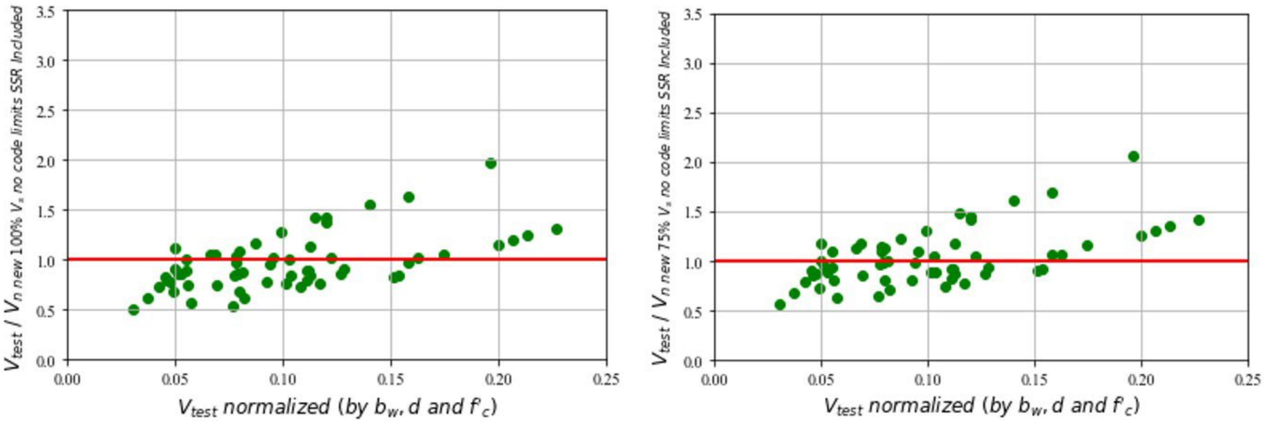

Figure 26: Influence of V_s contribution (α_3) on revised OWS relationships (code limits excluded)

Figure 26(a): $\alpha_3 = 1.00$ (figure on the left)

Figure 26(b): $\alpha_3 = 0.75$ (figure on the right)

4.4.4 Proposed Updates to The OWS Relationships

From the results obtained from the regression analysis, which was discussed earlier, it becomes evident that considering the SSR in the OWS relationships helps in lowering the dispersion and improving the accuracy of the predicted shear strength considerably.

Moreover, it was observed that using a reduction factor for V_s also helps in improving the accuracy of the predicted shear strength. This could be explained by the fact that the rebars that cross the cracks, deform, and are close to reach yielding will be engaged which could be addressed as the effective contribution from the transverse reinforcement to the overall OWS strength.

Although, the accuracy of the predicted values, even without the inclusion of the reduction factor for the proposed OWS relationship, is improved considerably compared to the ACI 318-19 provisions, it is recommended to consider applying a reduction factor to V_s to account for the effective shear contribution from the transverse reinforcement to obtain more accurate results. This reduction factor would not be constant. However, for simplicity and ease of use, a simplified reduction factor could be considered based on the results obtained from the regression analysis on the experimental data.

Another consideration which needs to be investigated is the impact of the ACI 318-19 limits on accuracy of the predicted OWS strength. The evaluation of the ACI 318-19 limits and their possible impact on the performance of the OWS shear relationships is discussed in the following section.

4.5 Evaluation of ACI 318-19 Limits and Their Impact on OWS Relationships

In this section, the ACI 318-19 limits on f_{yt}, f'_c, $V_{c,\ max}$, and V_s are evaluated. The SR is plotted as a function of the following parameters to reassess the limits for the proposed OWS relationships.

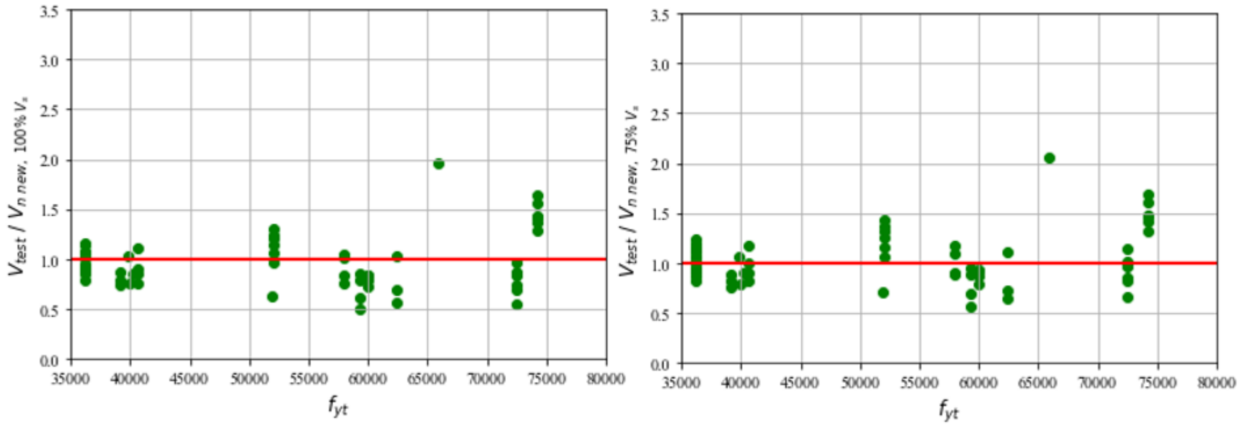

Figure 27: Impact of f_{yt} on SR using the proposed relationship (V_n) with 100% V_s

Figure 27(a): $\alpha_3 = 1.00$ (figure on the left)

Figure 27(b): $\alpha_3 = 0.75$ (figure on the right)

The current limit for yield stress of shear reinforcement, f_{yt}, in ACI 318-19 is 60,000 psi. However, ACI 318-19 has a more relaxed f_{yt} limit for special moment frames which is 80,000 psi per section 20.2.2.4. The maximum yield stress of transverse reinforcement for the specimens in the database is just below 80,000 psi. However, given there is no trend in SR with respect to f_{yt} even for the larger values, as shown in Figures 14 and 20, the ACI 318-19 limits are retained.

The maximum contribution from concrete ($V_{c,\,max}$) in ACI 318-19 is limited to $5\lambda\sqrt{f_c'}\,b_w d$ per section 22.5.5.1.1. Moreover, ACI 318-19 has an upper limit for the axial load ratio term in the V_c equation $(N_u/6A_g)$ which is $0.05f_c'$.

In order to investigate the impact of the ACI 318-19 limits on the accuracy of the predicted OWS strength, the limits were applied to the proposed OWS relationships, and the statistical parameters were calculated accordingly. A comparison between the statistical parameters for the predicted strength with and without the ACI 318-19 limits (presented in Table 7) suggest that the code limits are required to be re-evaluated.

Table 7: Evaluation of ACI 318-19 limits on the OWS strength (proposed relationships)

Method	SSR Considered (Yes/ No)	Code Limits Considered (Yes/ No)	Statistical Parameters			
			Mean	CV	R^2	RMSE
New $\alpha_3 = 1$	**Yes**	**No**	0.96	0.28	0.50	0.0287
New $\alpha_3 = 0.75$	**Yes**	**No**	1.04	0.27	0.73	0.0276
New $\alpha_3 = 1$	**Yes**	**Yes**	1.16	0.39	0.44	0.0393
New $\alpha_3 = 0.75$	**Yes**	**Yes**	1.26	0.37	0.65	0.0417

As shown in Table 7, there is a considerable improvement to CV, regardless of the α_3, when the code limits for $V_{c,\,max}$ $(5\lambda\sqrt{f_c'}\,b_w d)$ and the axial load term $(0.05f_c')$ are not considered. A comparison between Figures 26 and 28, also validates a significant improvement to the dispersion of the predicted values when the code limits are being excluded.

Therefore, in the next step the possibility for a more relaxed upper bound requirement for the $V_{c,max}$ and the axial load term was studied which is discussed in the following section.

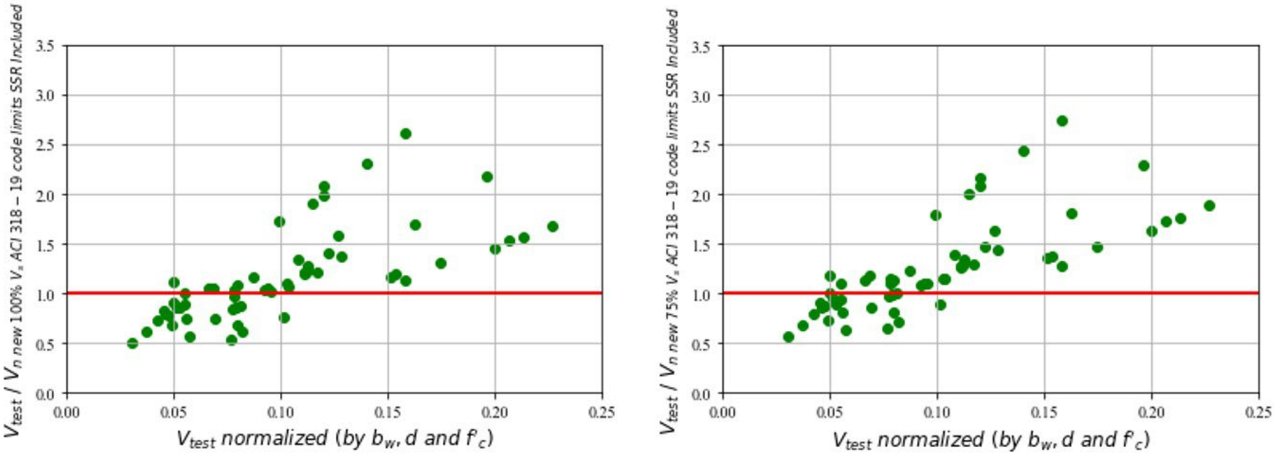

Figure 28: Influence of V_s contribution (α_3) on revised OWS relationships (code limits included)

Figure 28(a): $\alpha_3 = 1.00$ (figure on the left)

Figure 28(b): $\alpha_3 = 0.75$ (figure on the right)

4.6 Proposed OWS Relationships and The Revised Code Limits

The new proposed OWS relationship considers the SSR and the reduction factor on the V_s to improve the accuracy and minimize the dispersion as discussed in the previous sections.

The proposed OWS shear relationship, taking into account the considerations discussed in section 4.3 for the selection of the coefficients, is as follows:

$$V_n = V_c + \alpha_s V_s$$

$$V_s = \frac{A_v\, f_{yt}\, d}{s}$$

$$\left[\boldsymbol{\alpha_c}\lambda(\rho_w)^{\mathbf{1.25}}\, f'_c + \frac{N_u}{6A_g}\right] b_w d$$

Where:

- $\alpha_c = \begin{cases} 5.5 & \text{for } SSR \leq 2.0 \\ \text{linear interpolation} & \text{for } 2.0 < SSR < 3.0 \\ 1.5 & \text{for } SSR \geq 3.0 \end{cases}$
- $\alpha_s = 0.75$

The statistical evaluation suggests that some of the ACI 318-19 limits, as discussed in section 4.5, are over conservative and influence the accuracy of the predicted OWS strength for RC columns. Particularly, for the following upper bounds:

- $V_{c,max} \leq 5\lambda\sqrt{f'_c}\, b_w d$ per ACI 318-19 section 22.5.5.1.1
- $N_u/6A_g \leq 0.05\sqrt{f'_c}$ per ACI 318-19 section 22.5.5.1.2

The results from the study suggest that a larger scalar for these limits can significantly improve the accuracy of the predicted OWS strength. The results from the analysis indicate that the above-mentioned limits can be more relaxed as follows:

- $V_{c,max\ new} \leq 8\lambda\sqrt{f'_c}\, b_w d$ per ACI 318-19 section 22.5.5.1.1
- $N_u/6A_g \leq 0.07\sqrt{f'_c}$ per ACI 318-19 section 22.5.5.1.2

A comparison between the computed statistical parameters for the results with the ACI 318-19 limits, and the above-mentioned revised limits (using the proposed new OWS relationship), summarized in Table 8, confirm that the accuracy of the predicted values have been improved substantially.

Table 8: Evaluation of new code limits for $V_{c,\ max}$ and the axial load ratio term in V_c

Method	**SSR Considered (Yes/ No)**	**Code Limits Considered**	**Statistical Parameters**			
			Mean	**CV**	**R^2**	**RMSE**
New **$\alpha_3 = 0.75$**	**Yes**	**No** **Code Limits**	1.04	0.27	0.73	0.0276
New **$\alpha_3 = 0.75$**	**Yes**	**ACI 318-19 Limits**	1.26	0.37	0.65	0.0417
New **$\alpha_3 = 0.75$**	**Yes**	**New** **Proposed Limits**	1.05	0.26	0.73	0.0272

A comparison between Figures 29(a) and 29(b), graphically shows the significant improvement to the dispersion of the predicted values when the proposed code limits are being applied.

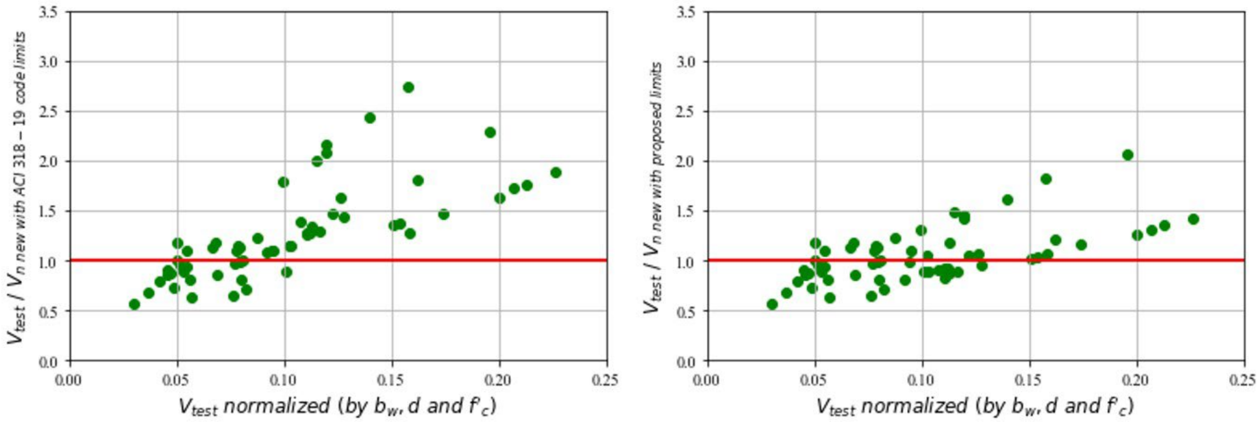

Figure 29: Evaluation of new code limits for $V_{c,\ max}$ and the axial load ratio term in V_c

Figure 29(a): with the application of ACI 318-19 code limits (figure on the left)

Figure 29(b): with the application of new proposed code limits (figure on the right)

A comparison between the proposed and ACI 318-19 OWS provisions, as shown numerically in Table 9 and graphically in Figure 30, indicates that there is a significant improvement to the predicted OWS strength for RC columns when the proposed provisions are used.

Table 9: Comparative evaluation of the proposed and ACI 318-19 OWS provisions

Method	**Code Limits Considered**	**Statistical Parameters**			
		Mean	**CV**	**R^2**	**RMSE**
ACI 318-19 (a)	**ACI 318-19 Limits**	1.26	0.50	0.350	0.0465
ACI 318-19 (b)	**ACI 318-19 Limits**	1.20	0.48	0.342	0.0456
Proposed	**Proposed Limits**	1.05	0.26	0.730	0.0272
% Improvement to ACI 318-19 (a) (if proposed relationships used)		**16.7%**	**48.0%**	**108.6%**	**41.5%**
% Improvement to ACI 318-19 (b) (if proposed relationships used)		**12.5%**	**45.8%**	**113.5%**	**40.4%**

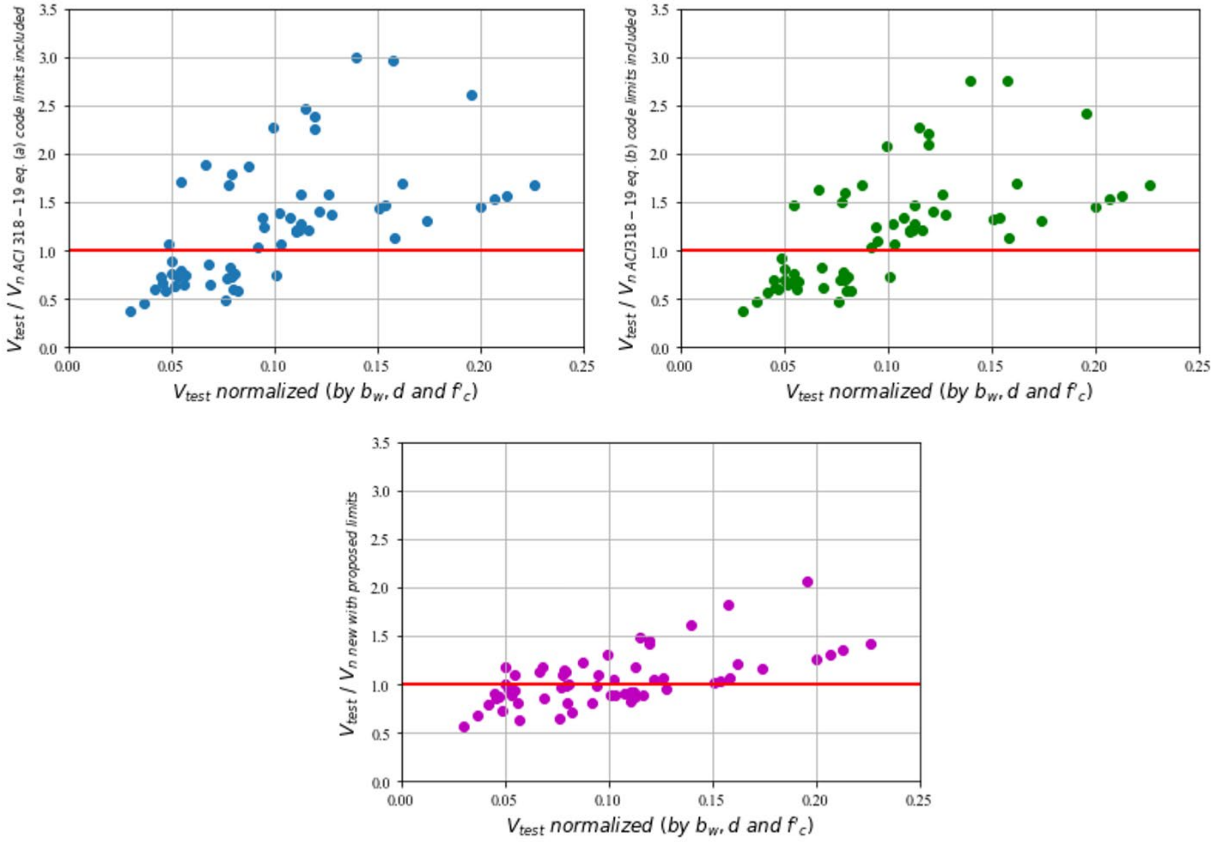

Figure 30: Comparative evaluation of the proposed and ACI 318-19 OWS provisions

Figure 30(a): Based on ACI 318-19 simplified method and the code limits (shown in blue)

Figure 30(b): Based on ACI 318-19 detailed method and the code limits (shown in green)

Figure 30(c): Based on the proposed method and the proposed code limits (shown in magenta)

Chapter 5: Summary and Recommendations

The objective of this research was to evaluate the predicted shear capacity of RC columns in moment frames under seismic loads, based on ACI 318-19 provisions, and propose the possible changes if deemed required. For this purpose, a column database was developed and used to evaluate the accuracy of the ACI 318-19 OWS provisions for non-prestressed RC columns. The results showed that the predicted shear strength based on the detailed approach is slightly better than the simplified approach. However, in both cases, the ACI 318-19 provisions significantly underpredict the actual shear capacity of the columns obtained from the test results with a considerable dispersion.

In order to improve the accuracy of the OWS provisions, the influence of f_c', f_{yt}, ρ_w, ALR and SSR on the predicted OWS strength, using the simplified and detailed approaches, was evaluated. There was no specific trend in SR with respect to f_c' or f_{yt}. However, it was observed that the predicted shear strength, using the simplified or detailed approach, is significantly lower than the expected shear strength, obtained from the test results, for members having ρ_w more than about 2.5% and the also when SSR is less than about 2.0.

The impact of SSR is not directly considered in the ACI 318-19 provisions. Therefore, the possible update to the OWS provisions to consider the higher shear strength for column with lower SSR was investigated. Based on the results from the regression analysis, a larger scalar value (introduced as α_c) when the SSR is less than 2.0 and a smaller scalar value when the SSR is more than 3.0 helped in improving the predicted shear strength significantly.

Several regression analyses were run for the optimization of the OWS provisions to improve the accuracy, starting from simple, evaluating the performance based on the new changes and adding more complexity to obtain a reasonable result. The evaluation and selection of the coefficients were based on balancing precision, ease of use while minimizing the changes where possible.

The 100% contribution from the transverse reinforcement is commonly considered in the ACI 318 provisions for RC members. However, in this study this contribution was evaluated for RC columns with the conditions discussed in section 2.4, along with the power of ρ_w and f'_c and the other coefficients. The possibility for updating the power of f'_c, in the V_c equation, from 0.5 to 1.0 was considered for ease of use and to avoid confusion for unit conversion.

The results from the regression analysis showed that the inclusion of the reduction factor has a noticeable influence on minimizing the dispersion of the predicted shear strength. It was observed that for the lowest CVs, the reduction factor was in the range of 0.6 to about 0.8. Eventually, a reduction factor of 0.75 was proposed to simplify the general form of the equation, for ease of use, without compromising the accuracy noticeably.

A new relationship for OWS strength for non-prestressed members was proposed, as shown below, which considers the influence of SSR and a reduction factor on V_s (α_s) to account for the effective contribution of the transverse reinforcement to the overall shear strength.

$$V_n = V_c + \alpha_s V_s$$

$$V_s = A_v f_{yt} \frac{d}{s}$$

$$\left[\boldsymbol{\alpha_c} \lambda (\rho_w)^{\mathbf{1.25}} f'_c + \frac{N_u}{6A_g}\right] b_w d$$

Where:

- $\alpha_c = \begin{cases} 5.5 & \text{for } SSR \leq 2.0 \\ \text{linear interpolation} & \text{for } 2.0 < SSR < 3.0 \\ 1.5 & \text{for } SSR \geq 3.0 \end{cases}$
- $\alpha_s = 0.75$

After identifying the required changes, the ACI limits were examined for possible updates to improve the accuracy of the predicted OWS strength. The results from the study, showed that a larger scalar for these limits can significantly improve the accuracy of the predicted shear strength. The following, more relaxed, limits for $V_{c,max}$ and the axial load term in the V_c equation were proposed, based on the results of the data analysis:

- $V_{c,max\ new} \leq 8\lambda\sqrt{f_c'}\, b_w d$
- $N_u/6A_g \leq 0.07\sqrt{f_c'}$

The OWS strength relationships for members with transverse reinforcement are developed and empirically validated by laboratory tests. Therefore, by including more experimental results in the data analysis, the accuracy of the relationships can be possibly improved further. For this purpose, further development of the column database is a project which is currently in progress to help with further validation and possible improvement of the RC column design relationships.

Moreover, the evaluation of the impact from the proposed provisions on the probabilistic safety parameters, such as safety index and probability of collapse, considering the overall structural system is another area of interest which could be explored in future studies.

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Appendix A: Column Shear Experimental Data

Table 10: Column shear experimental data (summary)

Count	**Reference Publication**	**Specimen ID**	**f'_c (psi)**	**$f_{y\_long.}$ (psi)**	**f_{yt} (psi)**	**h (in)**	**d (in)**	**b_w (in)**	**ρ_{w_long} (%)**	**d_{b_t} (in)**	**d_{b_long} (in)**	**ALR (%)**	**SSR**	**V_{test} (kip)**
1	Aboutaha et al., 1999	SC1	5040	58000	58000	18.00	16.14	36.00	1.94	0.38	1.00	10.0	2.7	132.9
2	Aboutaha et al., 1999	SC3	3170	58000	58000	18.00	16.14	36.00	1.94	0.38	1.00	10.0	2.7	101.2
3	Aboutaha et al., 1999	SC4	3170	58000	58000	18.00	16.14	36.00	1.94	0.38	1.00	10.0	2.7	125.9
4	Aboutaha et al., 1999	SC9	2325	58000	58000	36.00	34.14	18.00	1.94	0.38	1.00	10.0	1.3	144.5
5	Aman et al., 1991	CB060C	6846	60002	60002	10.94	9.86	10.94	4.12	0.24	0.51	7.4	1.2	113.7
6	Aman et al., 1991	CB07T06C	6846	60002	60002	10.94	9.86	10.94	4.12	0.24	0.51	7.3	1.2	111.6
7	Arakawa et al., 1989	0A1	5092	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	-6.7	1.0	15.7
8	Arakawa et al., 1989	0A0	4580	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	0.0	1.0	22.5
9	Arakawa et al., 1989	0A2	4608	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	14.8	1.0	29.2
10	Arakawa et al., 1989	0A4	4907	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	27.8	1.0	33.7

Table 10: Column shear experimental data (summary)- continued

Count	**Reference Publication**	**Specimen ID**	**f'_c**	**$f_{y\_long.}$**	**f_{yt}**	**h**	**d**	**b_w**	**ρ_{w_long}**	**d_{b_t}**	**d_{b_long}**	**ALR**	**SSR**	**V_{test}**
			(psi)	**(psi)**	**(psi)**	**(in)**	**(in)**	**(in)**	**(%)**	**(in)**	**(in)**	**(%)**		**(kip)**
11	Arakawa et al., 1989	0A5	4794	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	35.6	1.0	30.3
12	Arakawa et al., 1989	2A0	4622	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	0.0	1.0	20.2
13	Arakawa et al., 1989	2A2	4679	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	14.6	1.0	24.7
14	Arakawa et al., 1989	2A4	4466	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	30.6	1.0	28.1
15	Arakawa et al., 1989	2A5	4380	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	39.0	1.0	31.5
16	Arakawa et al., 1989	4A1	4395	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	-7.8	1.0	16.4
17	Arakawa et al., 1989	4A0	4921	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	0.0	1.0	22.0
18	Arakawa et al., 1989	4A2	4367	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	15.6	1.0	25.2
19	Arakawa et al., 1989	4A4	4580	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	29.8	1.0	28.6
20	Arakawa et al., 1989	4A5	4438	36127	36127	8.86	7.93	7.09	2.62	0.16	0.51	38.5	1.0	27.7

Table 10: Column shear experimental data (summary)- continued

Count	**Reference Publication**	**Specimen ID**	**f'_c (psi)**	**$f_{y\_long.}$ (psi)**	**f_{yt} (psi)**	**h (in)**	**d (in)**	**b_w (in)**	**ρ_{w_long} (%)**	**d_{b_t} (in)**	**d_{b_long} (in)**	**ALR (%)**	**SSR**	**V_{test} (kip)**
21	Araki, 2004	FS27CA	3931	51924	51924	31.50	30.37	31.50	1.23	0.63	0.98	26.6	1.5	309.1
22	Chiu et al., 2019	FSF-15S-0.1	5018	40611	40611	15.75	13.35	15.75	2.85	0.39	0.87	10.0	4.5	52.7
23	Chiu et al., 2019	SF-30S-0.1	4946	40611	40611	15.75	13.35	15.75	2.85	0.39	0.87	10.0	4.5	51.9
24	Chiu et al., 2019	FSF-15S-0.2	4467	40611	40611	15.75	13.35	15.75	2.85	0.39	0.87	20.0	4.5	52.7
25	Chiu et al., 2019	SF-30S-0.2	4815	40611	40611	15.75	13.35	15.75	2.85	0.39	0.87	20.0	4.5	53.6
26	Flores, 2004	1	6000	59901	59901	6.00	5.02	6.00	2.45	0.13	0.38	13.9	3.4	8.3
27	Flores, 2004	2	6000	59901	59901	6.00	5.02	6.00	2.45	0.13	0.38	13.9	3.4	7.6
28	Hendrix, 2010	NS-NWB	4003	62366	62366	20.98	18.75	20.98	3.45	0.38	1.27	10.0	2.6	150.0
29	Hendrix, 2010	HS-NWB	7803	62366	62366	20.98	18.75	20.98	3.45	0.38	1.27	5.1	2.6	150.0
30	Hendrix, 2010	HS-NWD	7803	62366	62366	20.98	18.75	20.98	3.45	0.38	1.27	5.1	2.6	175.0

Table 10: Column shear experimental data (summary)- continued

Count	Reference Publication	Specimen ID	f'_c (psi)	$f_{y\_long.}$ (psi)	f_{yt} (psi)	h (in)	d (in)	b_w (in)	ρ_{w_long} (%)	d_{b_t} (in)	d_{b_long} (in)	ALR (%)	SSR	V_{test} (kip)
31	Hosoya et al., 1992	4	4192	52069	52069	9.84	8.16	9.84	2.43	0.25	0.50	29.3	1.3	53.3
32	Hosoya et al., 1992	5	4380	52069	52069	9.84	8.16	9.84	2.43	0.25	0.50	36.3	1.3	72.8
33	Hosoya et al., 1992	6	4250	52069	52069	9.84	8.16	9.84	2.43	0.25	0.50	36.4	1.3	68.3
34	Hosoya et al., 1992	10	4409	52069	52069	9.84	8.16	9.84	2.43	0.25	0.50	32.5	1.3	61.8
35	Hosoya et al., 1992	11	4279	52069	52069	9.84	8.17	9.84	2.43	0.25	0.50	35.6	1.3	73.3
36	Hosoya et al., 1992	12	4322	52069	52069	9.84	8.17	9.84	2.43	0.25	0.50	37.1	1.3	78.7
37	Huang et al., 2020	CM1	5366	59293	59293	9.84	8.70	9.84	1.29	0.24	0.63	17.3	4.2	23.7
38	Huang et al., 2020	CM2	5366	59293	59293	9.84	8.70	9.84	1.29	0.24	0.63	17.3	4.2	13.9
39	Huang et al., 2020	CM3	5366	59293	59293	9.84	8.70	9.84	1.29	0.24	0.63	17.3	4.2	21.8
40	Huang et al., 2020	CM4	5366	59293	59293	9.84	8.70	9.84	1.29	0.24	0.63	17.3	4.2	17.0

Table 10: Column shear experimental data (summary)- continued

Count	**Reference Publication**	**Specimen ID**	**f'_c (psi)**	**$f_{y\_long.}$ (psi)**	**f_{yt} (psi)**	**h (in)**	**d (in)**	**b_w (in)**	**ρ_{w_long} (%)**	**d_{b_t} (in)**	**d_{b_long} (in)**	**ALR (%)**	**SSR**	**V_{test} (kip)**
41	Jin et al., 2015	HC4	10588	74259	74259	5.91	4.69	11.81	2.79	0.24	0.79	9.1	1.7	81.9
42	Jin et al., 2015	HC5	10588	74259	74259	5.91	4.69	11.81	2.79	0.24	0.79	13.1	1.7	92.6
43	Jin et al., 2015	HC6	10588	74259	74259	5.91	4.69	11.81	2.79	0.24	0.79	9.1	2.2	58.2
44	Jin et al., 2015	HC7	10588	74259	74259	5.91	4.69	11.81	2.79	0.24	0.79	13.1	2.2	70.1
45	Jin et al., 2015	HC8	10588	74259	74259	5.91	4.69	11.81	2.79	0.24	0.79	13.1	2.2	70.1
46	Jin et al., 2015	HC9	10588	74259	74259	5.91	4.69	11.81	2.79	0.24	0.79	9.1	2.2	67.4
47	Jin et al., 2015	PC2	4931	65847	65847	5.91	4.69	11.81	2.79	0.24	0.79	13.1	2.2	53.5
48	Kim et al., 2018	SL00S1B	4641	72519	72519	15.75	13.17	15.75	2.53	0.50	1.00	17.0	3.0	76.2
49	Kim et al., 2018	SL30S1B	4641	72519	72519	15.75	13.17	15.75	2.53	0.50	1.00	17.0	3.0	66.3
50	Kim et al., 2018	SL40S1B	4641	72519	72519	15.75	13.17	15.75	2.53	0.50	1.00	17.0	3.0	78.1

Table 10: Column shear experimental data (summary)- continued

Count	Reference Publication	Specimen ID	f'_c (psi)	$f_{y\_long.}$ (psi)	f_{yt} (psi)	h (in)	d (in)	b_w (in)	ρ_{w_long} (%)	d_{b_t} (in)	d_{b_long} (in)	ALR (%)	SSR	V_{test} (kip)
51	Kim et al., 2019c	SAd2	4641	72519	72519	15.75	13.18	15.75	2.45	0.50	0.98	17.0	3.0	74.4
52	Kim et al., 2019c	SBd2	4641	72519	72519	15.75	13.18	15.75	2.45	0.50	0.98	17.0	3.0	76.2
53	Kim et al., 2019c	SBd4	4641	72519	72519	15.75	13.18	15.75	2.45	0.50	0.98	17.0	3.0	73.7
54	Kim et al., 2019c	SCd2	4641	72519	72519	15.75	13.18	15.75	2.45	0.50	0.98	17.0	3.0	77.1
55	Kim et al., 2019c	SDd2	4641	72519	72519	15.75	13.18	15.75	2.45	0.50	0.98	10.0	3.0	75.5
56	Lam et al., 2003	X-3	4630	39740	39740	10.51	9.96	10.51	3.03	0.16	0.47	40.0	1.5	78.7
57	Lam et al., 2003	X-4	4630	39885	39885	6.30	5.75	6.30	3.53	0.16	0.47	65.2	3.0	19.6
58	Lam et al., 2003	X-6	4630	40176	40176	6.30	5.75	6.30	3.53	0.16	0.47	45.3	3.0	17.3
59	Lam et al., 2003	X-7	5181	39160	39160	6.30	5.75	6.30	3.53	0.16	0.47	45.1	3.0	17.3
60	Lam et al., 2003	X-8	5181	39160	39160	10.51	9.96	10.51	3.03	0.16	0.47	40.1	1.5	58.5
61	Lam et al., 2003	X-9	5181	39160	39160	10.51	9.96	10.51	3.03	0.16	0.47	40.1	1.5	68.6