New Equations to Estimate Reinforced Concrete Wall Shear Strength Derived from Machine Learning and Statistical Methods

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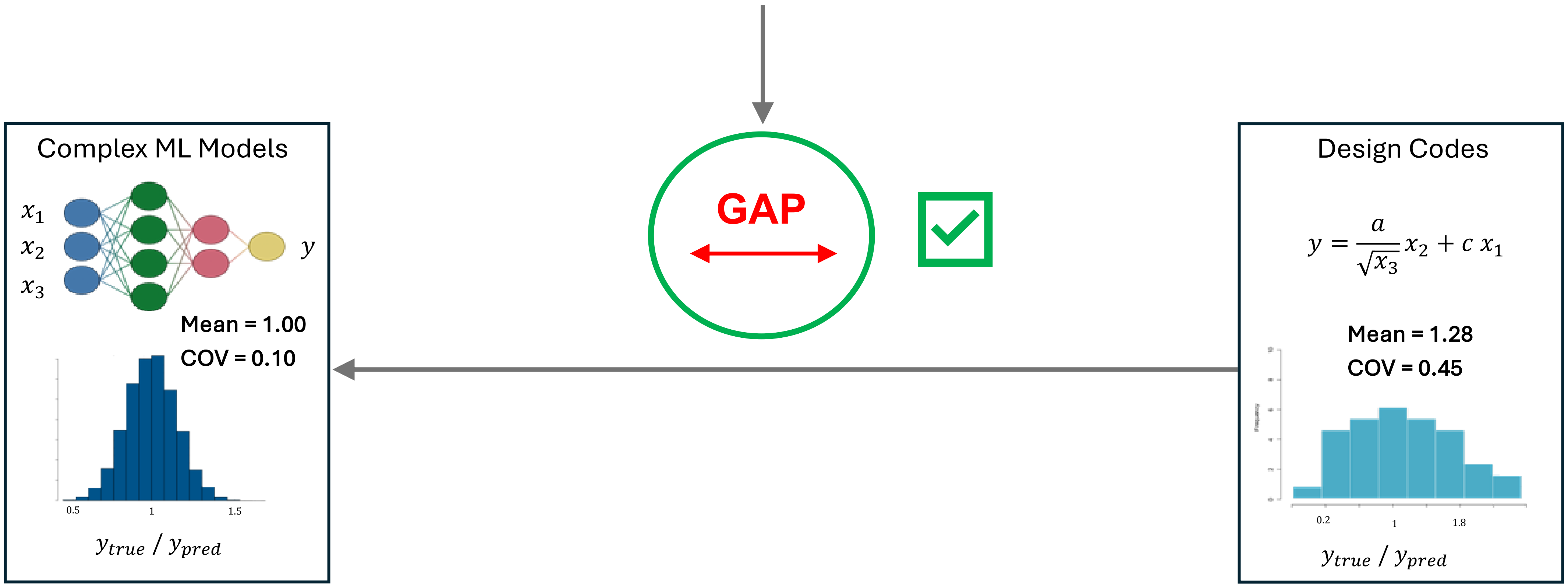
Outline

- Definition of Model Performance Requirements
- Definition of Equation Format
- Obtained and Proposed Models
- Details on the Analysis and Application of the Proposed Model

1. Definition of Model Performance Requirements

Framework by Rojas-Leon et al. (2024)



1. Definition of Model Performance Requirements

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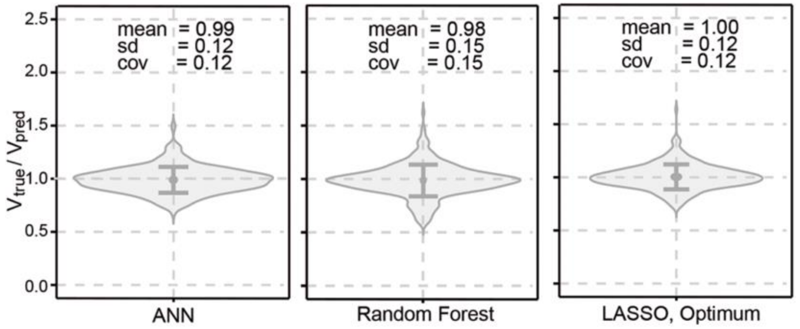
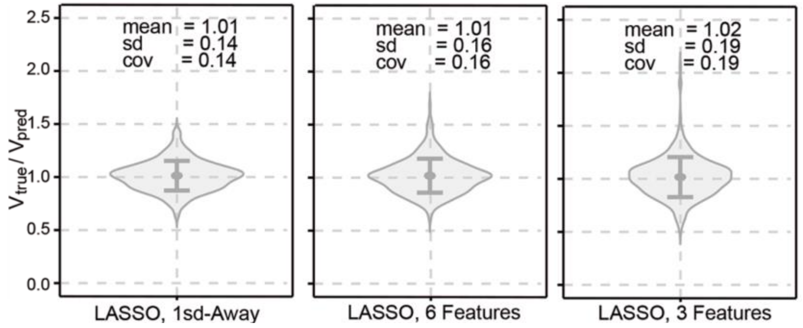


Complex Models



Simplified Models

Model	Statistics for V_{true}/V_{pred}		
	Mean	Median	COV
ACI 318-19, Chapter 18	1.26	1.17	0.42
ACI 318-11, Chapter 11	1.18	1.12	0.34
ASCE/SEI 43-05	1.26	1.25	0.29
AIJ 1999	0.73	0.74	0.31
NZS 3101:2006 – Simple	1.63	1.46	0.45
NZS 3101:2006 – Detailed	1.26	1.21	0.33

Design Codes

Requirements	Model Complexity Level	
	Complex ML Models	Simplified Models
Number of parameters	-	~ 3 – 6
V_{true}/V_{pred} mean ratio	0.99 – 1.01	0.98 – 1.02
COV	≤ 0.12	0.16 – 0.19
Train. Vs. Test. Error Margin	±20% of the converging error	±10% of the converging error

2. Definition of Equation Format

"$V_n = V_c + V_s$" format

$$V_n = \beta_0 V_c + \sum_{i}^{N_i} \beta_i \left(\prod_{j}^{N_j} \gamma_{j,i} \right) V_i$$

- Identification of main parameters
- Normalization

$$y_n = \beta_0 + \beta_1 \left(\frac{M_u}{V_u l_w}\right)^{a_c} \left(1 + \frac{P_u}{A_g' f_c'}\right)^{b_c} \left(\frac{h_w}{l_w}\right)^{c_c}$$

$$+ \beta_2 \left(\frac{M_u}{V_u l_w}\right)^{a_{be}} \left(1 + \frac{P_u}{A_g' f_c'}\right)^{b_{be}} \left(\frac{h_w}{l_w}\right)^{c_{be}} \frac{\rho_{be} f_{ybe}}{f_c'} \frac{A_{be}}{A_g'}$$

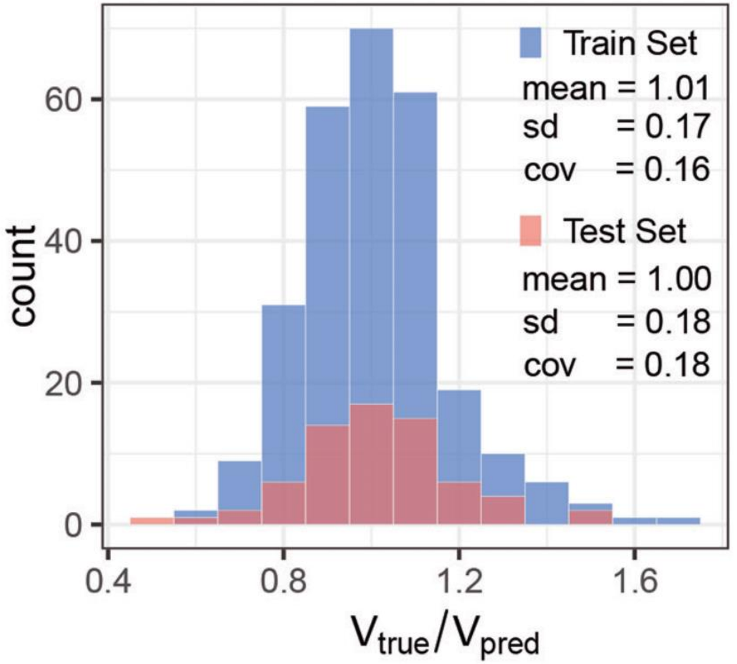
$$+ \beta_3 \left(\frac{M_u}{V_u l_w}\right)^{a_{wh}} \left(1 + \frac{P_u}{A_g' f_c'}\right)^{b_{wh}} \left(\frac{h_w}{l_w}\right)^{c_{wh}} \frac{\rho_{wh} f_{ywh}}{f_c'} \frac{A_{cv}}{A_g'}$$

$$+ \beta_4 \left(\frac{M_u}{V_u l_w}\right)^{a_{wv}} \left(1 + \frac{P_u}{A_g' f_c'}\right)^{b_{wv}} \left(\frac{h_w}{l_w}\right)^{c_{wv}} \frac{\rho_{wv} f_{ywv}}{f_c'} \frac{A_{cv}}{A_g'}$$

3. Obtained Equations

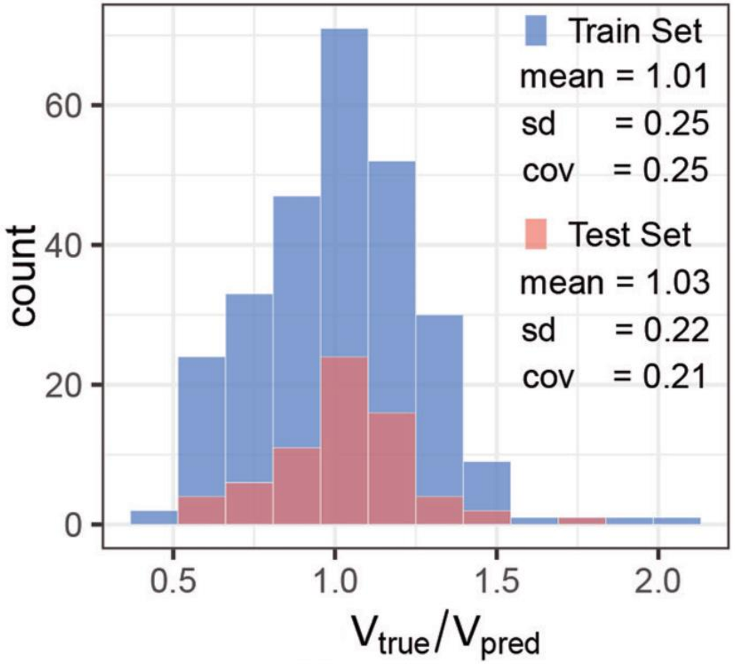
$$V_n = \alpha_c A_g' f_c' + \alpha_s(\rho_{sb} f_{ysb} + \rho_{wh} f_{ywh}) A_{cv}$$

$$\alpha_c = \frac{1}{100}\left(9\frac{\left(1+\frac{P_u}{A_g' f_c'}\right)^3}{\left(\frac{M_u}{V_u l_w}\right)^{1/3}} - 6\right), \quad \alpha_s = \frac{2}{5\left(\frac{M_u}{V_u l_w}\right)^{1/3}}$$



$$V_n = \alpha_c A_g' f_c' + \alpha_s \rho_{wh} f_{ywh} A_{cv}$$

$$\alpha_c = \frac{\left(\frac{\rho_{sb} f_{ysb}}{f_c'}\right)^{1/4}}{6\left(\frac{M_u}{V_u l_w}\right)^{1/2}}, \quad \alpha_s = \frac{2}{3}\left(\frac{\rho_{sb} f_{ysb}}{f_c'}\right)^{1/3}$$



We have the equation, but…

- Does it make sense?
- How to apply it in practice?
    - Use for walls with asymmetrical cross sections?
    - Parameter limitations?
    - Upper limit?
    - Strength reduction factor?
    - Detailed comparison with current equations?
    - Examples of application and its impact?

4. Proposed Model

18.10.4 *Shear strength*

18.10.4.1 V_n shall be calculated by:

$$V_n = (\alpha_c \lambda \sqrt{f_c'} + \rho_t f_{yt}) A_{cv} \qquad (18.10.4.1)$$

where:
$\alpha_c = 3$ for $h_w/\ell_w \leq 1.5$
$\alpha_c = 2$ for $h_w/\ell_w \geq 2.0$
It shall be permitted to linearly interpolate the value of α_c between 3 and 2 for $1.5 < h_w/\ell_w < 2.0$.

18.10.4.5 For horizontal wall segments and coupling beams, V_n shall not be taken greater than $10\sqrt{f_c'} A_{cv}$, where A_{cw} is the area of concrete section of a horizontal wall segment or coupling beam.

Shear strength:

$$V_n = \alpha_c A_g' f_c' + \alpha_s (\rho_{sb} f_{ysb} + \rho_{wh} f_{ywh}) A_{cv}$$

where:

$$\alpha_c = \frac{1}{100}\left(9\frac{\left(1 + \frac{P_u}{A_g' f_c'}\right)^3}{\left(\frac{M_u}{V_u l_w}\right)^{1/3}} - 6 \right), \quad \alpha_s = \frac{2}{5\left(\frac{M_u}{V_u l_w}\right)^{1/3}}$$

and

$$0 \leq P_u/(A_g' f_c') \leq 0.20, \quad A_g'/A_{cv} \leq 1.5, \quad 0.010 \leq \alpha_c \leq 0.100, \quad 0.30 \leq \alpha_s \leq 0.50$$

Upper limit:

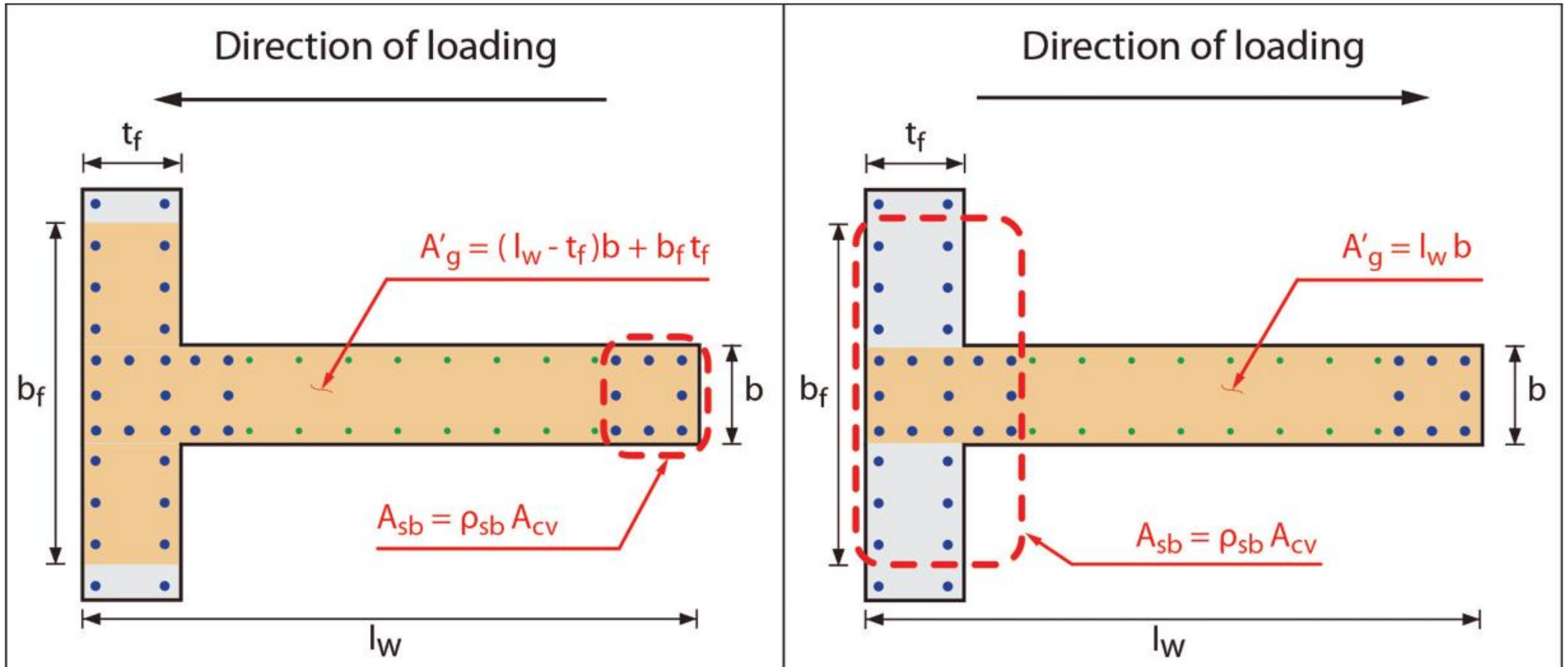
$$v_n = \frac{V_n}{A_{cv}} \leq \alpha_{shape} 10\sqrt{f_c'}$$

where:

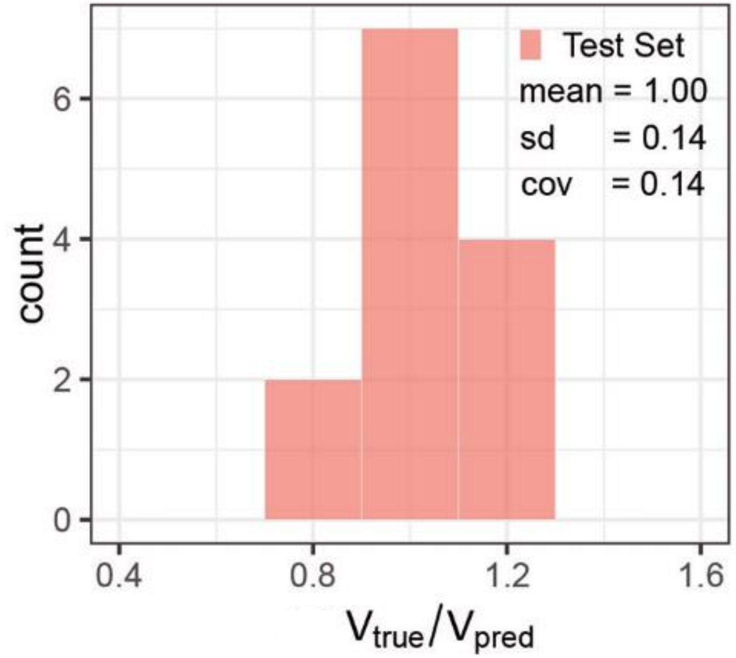
$$\alpha_{shape} = 0.7(1 + b_f t_f / A_{cv})^2, \quad 1.0 \leq \alpha_{shape} \leq 1.5$$

Application on Wall with Asymmetrical Cross Section

$$Prop.Eq.: V_n = \alpha_c A'_g f'_c + \alpha_s(\rho_{sb} f_{ysb} + \rho_{wh} f_{ywh}) A_{cv}$$



(a) Flange in Compression	(b) Flange in Tension
$A'_g = b_f t_f + (l_w - t_f)b \le 1.5A_{cv}$	$A'_g = l_w b$
A_{sb} = All the area of longitudinal reinforcement at the <u>right</u> side in this case	A_{sb} = Area of longitudinal reinforcement at the <u>left</u> side in this case, excluding one layer of bars at each side of the flange

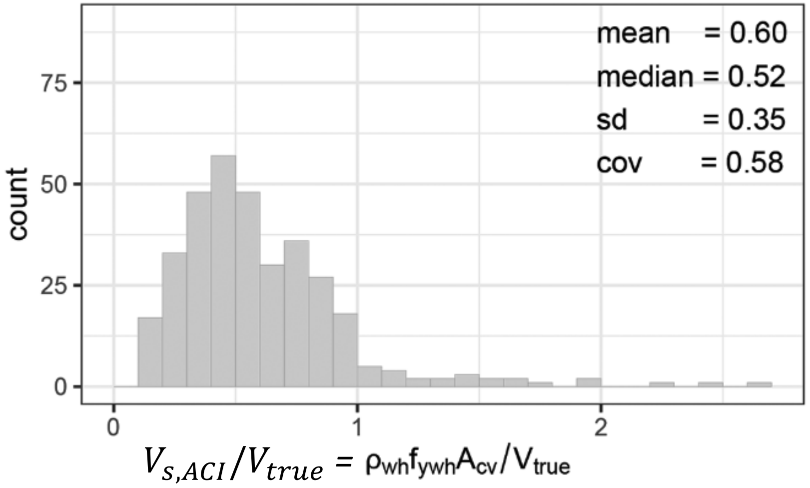


Vs Contribution

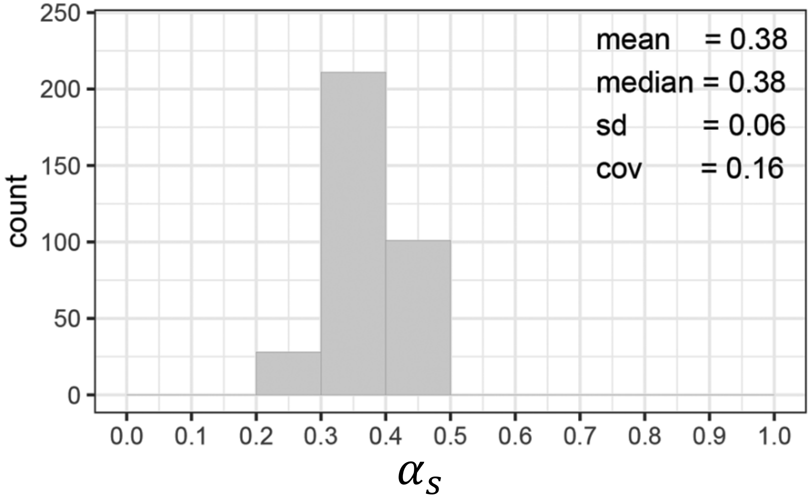
$ACI: \quad V_n = \alpha_c \lambda \sqrt{f_c'} A_{cv} + \rho_{wh} f_{ywh} A_{cv}$

$Prop.Eq.: V_n = \alpha_c A_g' f_c' + \alpha_s (\rho_{sb} f_{ysb} + \rho_{wh} f_{ywh}) A_{cv}$

V_s contribution as per ACI 318



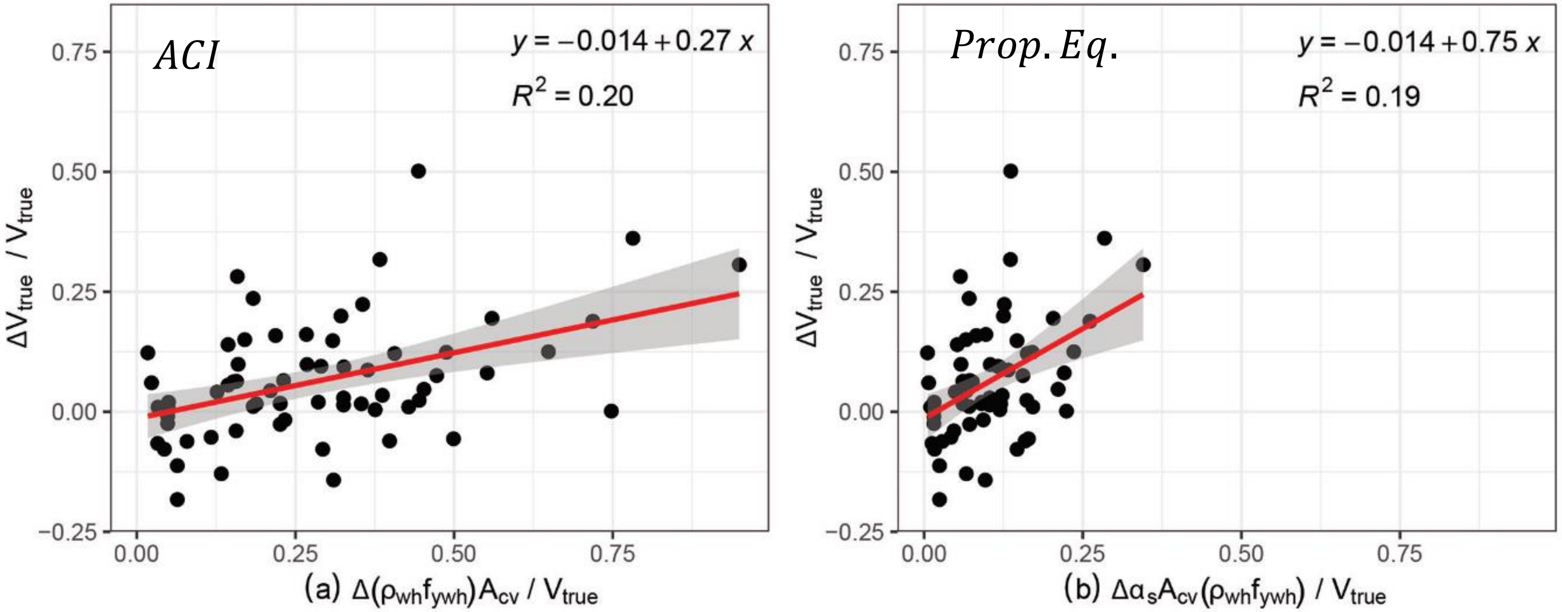
α_s in Proposed Eq.



*Companion Group Test 1: Changes **only in** $\rho_{wh} f_{ywh} A_{cv}$*

$ACI \longrightarrow \Delta V_n = \Delta(\rho_{wh} f_{ywh} A_{cv})$

$Prop.Eq. \rightarrow \Delta V_n = \Delta(\alpha_s \rho_{wh} f_{ywh} A_{cv})$

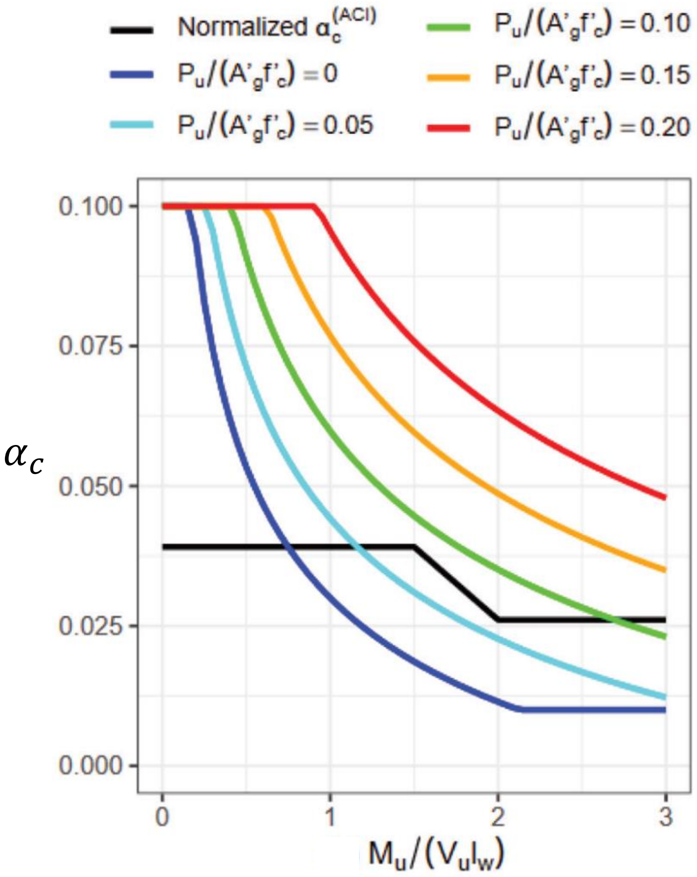


Vc Contribution

$ACI: \quad V_n = \alpha_c \lambda \sqrt{f_c'} A_{cv} + \rho_{wh} f_{ywh} A_{cv}$

$Prop.Eq.: V_n = \alpha_c A_g' f_c' + \alpha_s (\rho_{sb} f_{ysb} + \rho_{wh} f_{ywh}) A_{cv}$

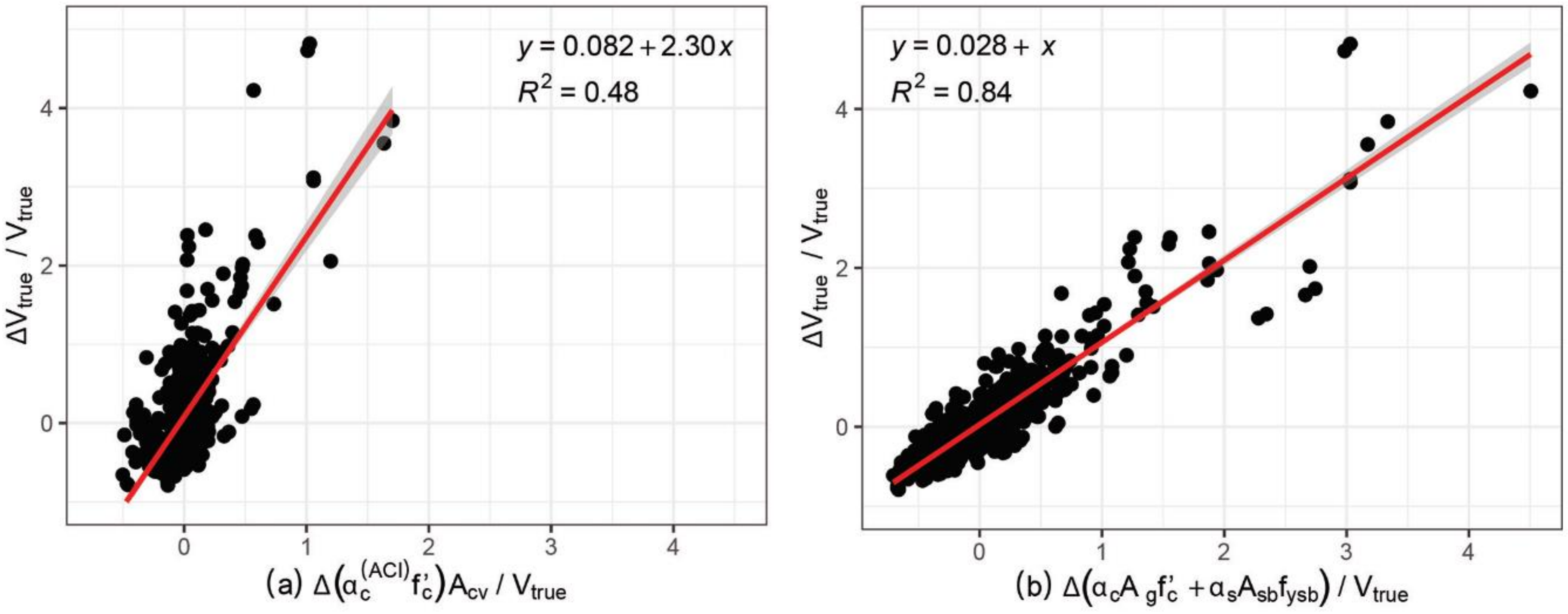
Comparison of α_c coefficients



Companion Group Test 2: ***No changes*** *in* $\rho_{wh} f_{ywh} A_{cv}$

$ACI \longrightarrow \quad \Delta V_n = \Delta\left(\alpha_c \lambda \sqrt{f_c'} A_{cv}\right)$

$Prop.Eq. \rightarrow \quad \Delta V_n = \Delta\left(\alpha_c A_g' f_c' + \alpha_s \rho_{sb} f_{ysb} A_{cv}\right)$



Upper Limit for Shear Strength

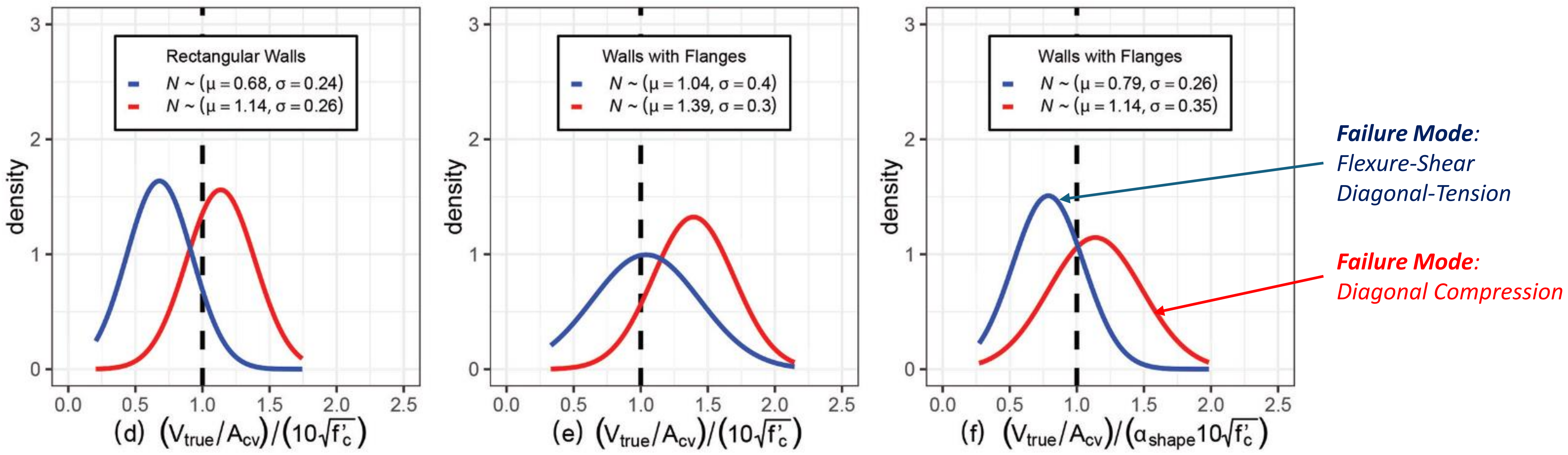
18.10.4.5 For horizontal wall segments and coupling beams, V_n shall not be taken greater than $\mathbf{10\sqrt{f_c'}A_{cv}}$, where A_{cw} is the area of concrete section of a horizontal wall segment or coupling beam.

→

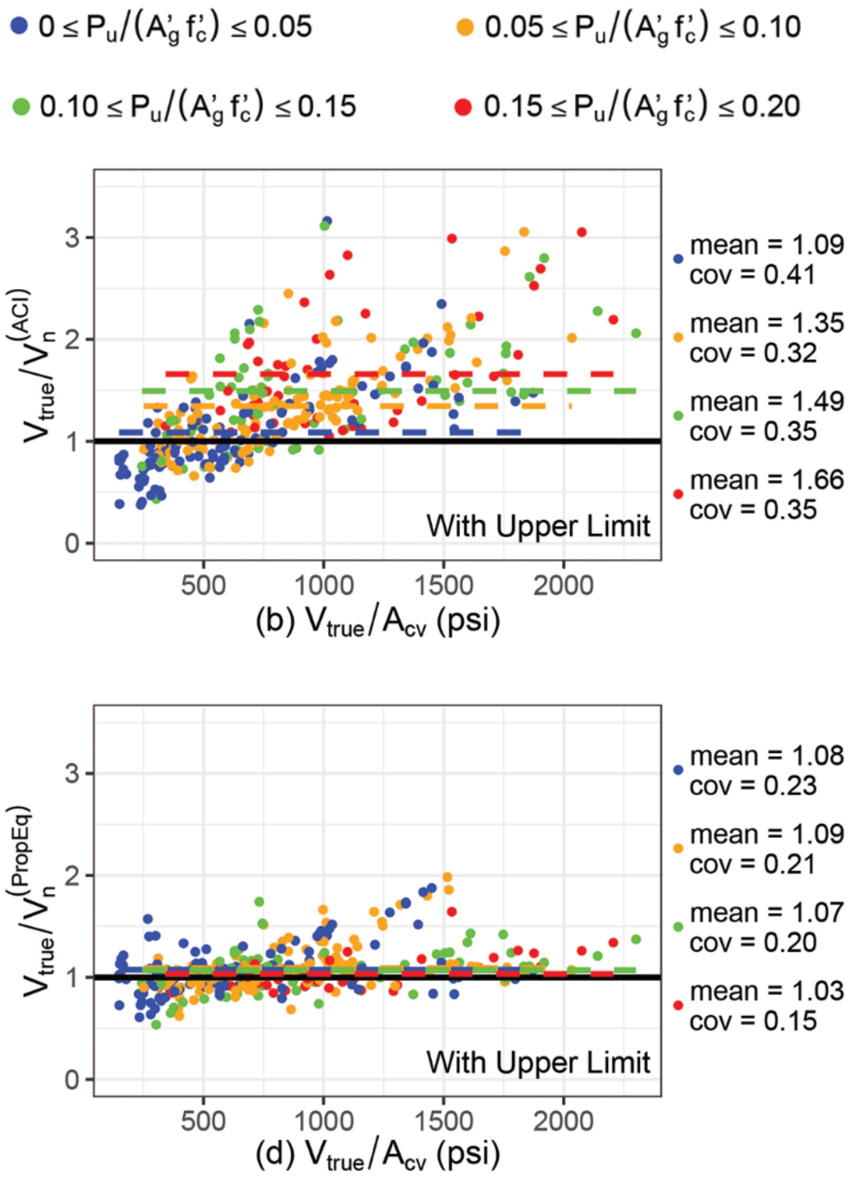
$$v_n = \frac{V_n}{A_{cv}} \leq \alpha_{shape} 10\sqrt{f_c'}$$

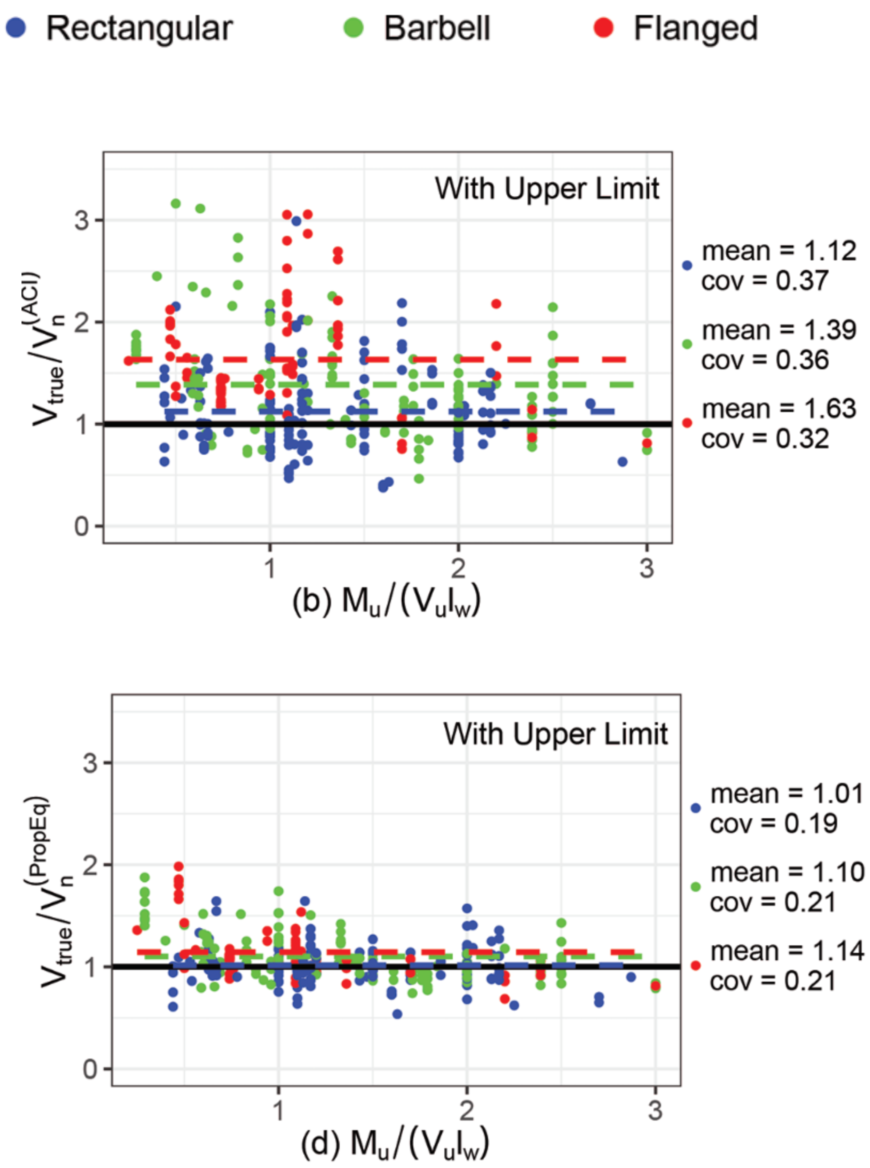
where:

$$\alpha_{shape} = 0.7(1 + b_f t_f / A_{cv})^2 \qquad 1.0 \leq \alpha_{shape} \leq 1.5$$



More Comparisons





Implementation in Codes / Standards

Bias factor (B) modification

Where calculated concrete compressive strains $\bar{\varepsilon}_c \leq 0.005$ and calculated longitudinal reinforcement tensile strains $\bar{\varepsilon}_s \leq 0.01$ at all points along a cross section of a wall, the B-value for shear can be determined as:

$$\left.\begin{array}{l} B = 1.35 \text{ for rectangular walls} \\ B = 1.35 \text{ for flanged walls with } b_{cf}t_{cf} \leq 0.05A_{cv} \\ B = 1.60 \text{ for flanged walls with } b_{cf}t_{cf} \geq 0.20A_{cv} \\ \text{Linear Interpolation can be used for } 0.05 < b_{cf}t_{cf} < 0.20. \end{array}\right\} \quad \text{(A-1a)}$$

Shear strength upper limit modification

For all vertical wall segments sharing a common lateral force, V_n shall not be taken greater than the sum of $\alpha_{sh}\, 8\sqrt{f_c'}A_{cv}$ for these wall segments, where α_{sh} for each vertical wall segment is determined as:

$$\alpha_{sh} = 0.7\left(1 + \frac{b_{fc}t_{fc}}{A_{cv}}\right)^2 \leq 1.2 \qquad \text{Eq. (D1)}$$

Where b_{fc} is the effective compression flange width determined according to 18.10.5.2 (intended to be taken as the web width plus overhanging flange). The value of α_{sh} in Eq. (D1) need not be taken less than 1.0. It is noted that use of α_{sh}= 1.0 for all wall segments is acceptable (conservative).