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Simplified shear strength model of RC slender walls

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Presenter : Sung Hyun Kim (Ph.D)

Soongsil University

School of Architecture

SOONGSIL UNIVERSITY 1897

American Concrete Institute

Research backgrounds

American Concrete Institute

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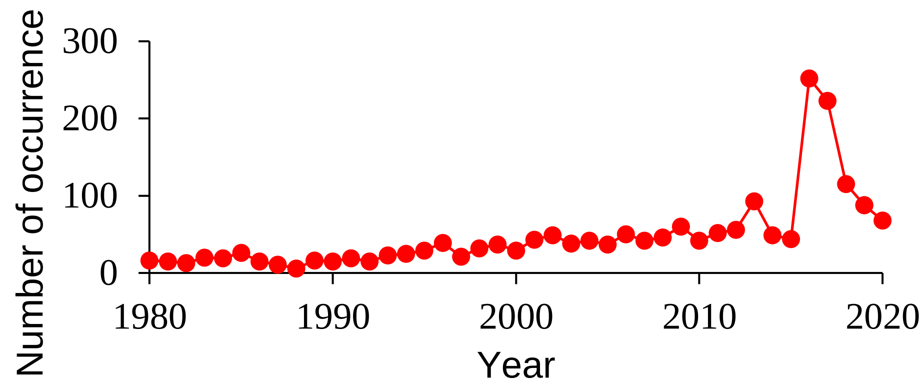
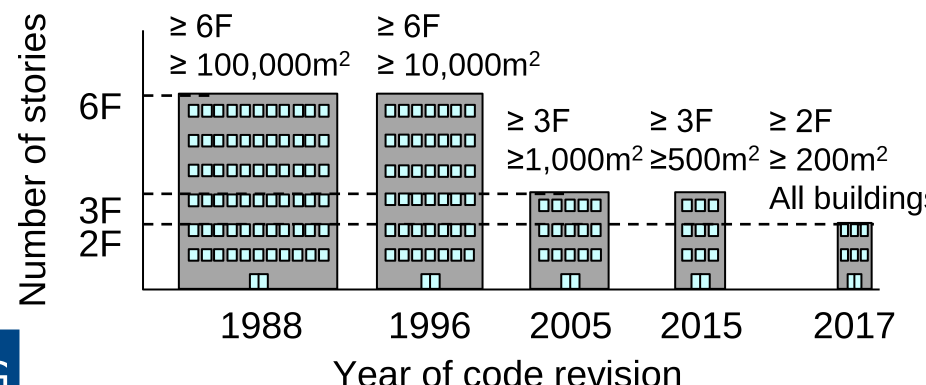
Background

- Earthquakes in worldwide caused damages on the RC structure.
- RC walls can be failed by severe shear damages by earthquake loads.
- The occurrence and magnitude of earthquakes have been gradually increased.
- The seismic design codes have been strengthened to address the increasing seismic hazard.

Structural damages by Earthquake



Occurrence of earthquakes in Korea



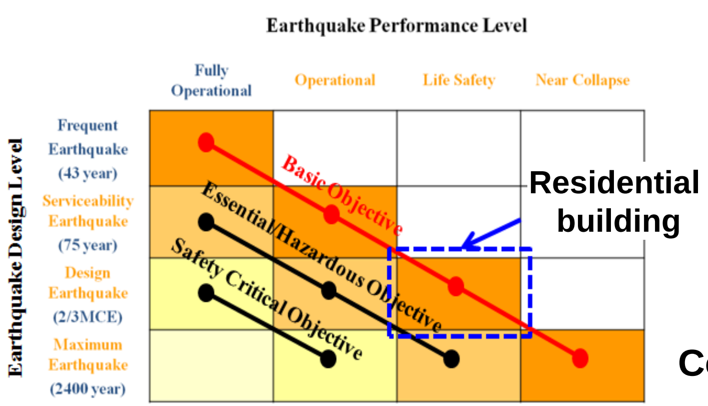
Buildings subject to seismic design obligations

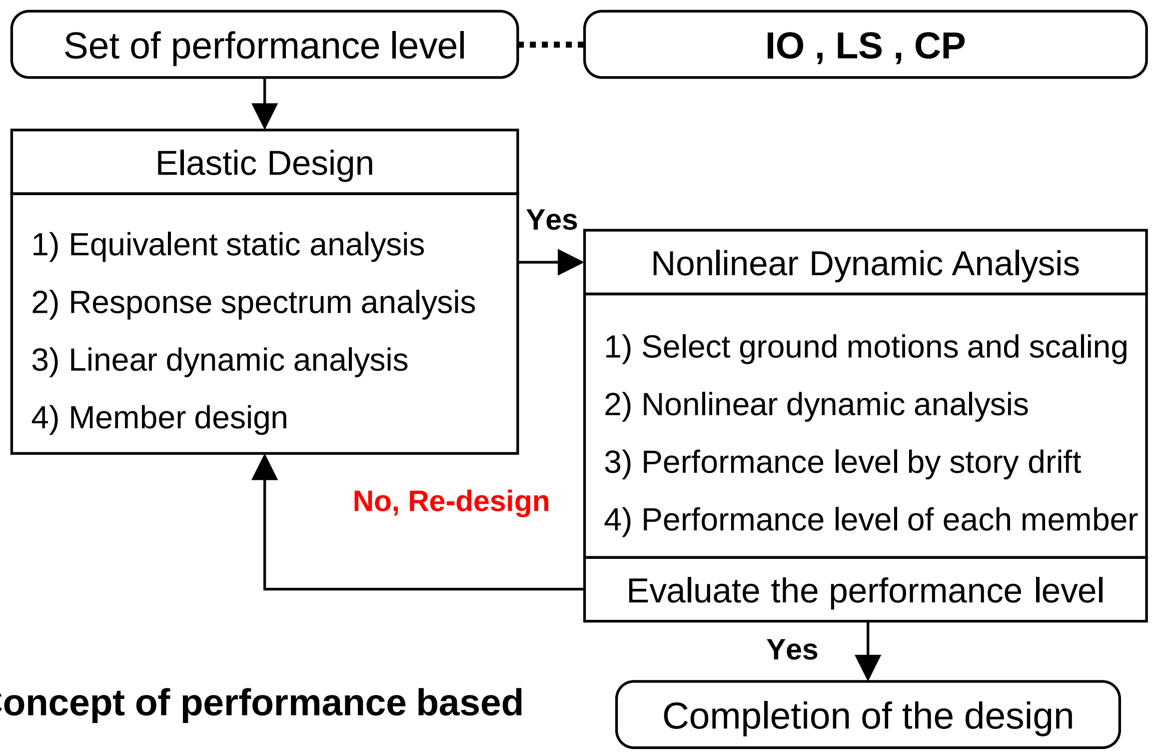
Performance based seismic design/evaluation (PBD)

- A performance based seismic design/evaluation method (PBD) is frequently used for

  1) economic seismic design of new RC buildings

  2) seismic performance evaluation and seismic retrofit of the existing RC buildings.
- In PBD, the performance of structural members is evaluated by the nonlinear analysis.
- It is required to evaluate the strength-deformation capacity of RC members accurately.

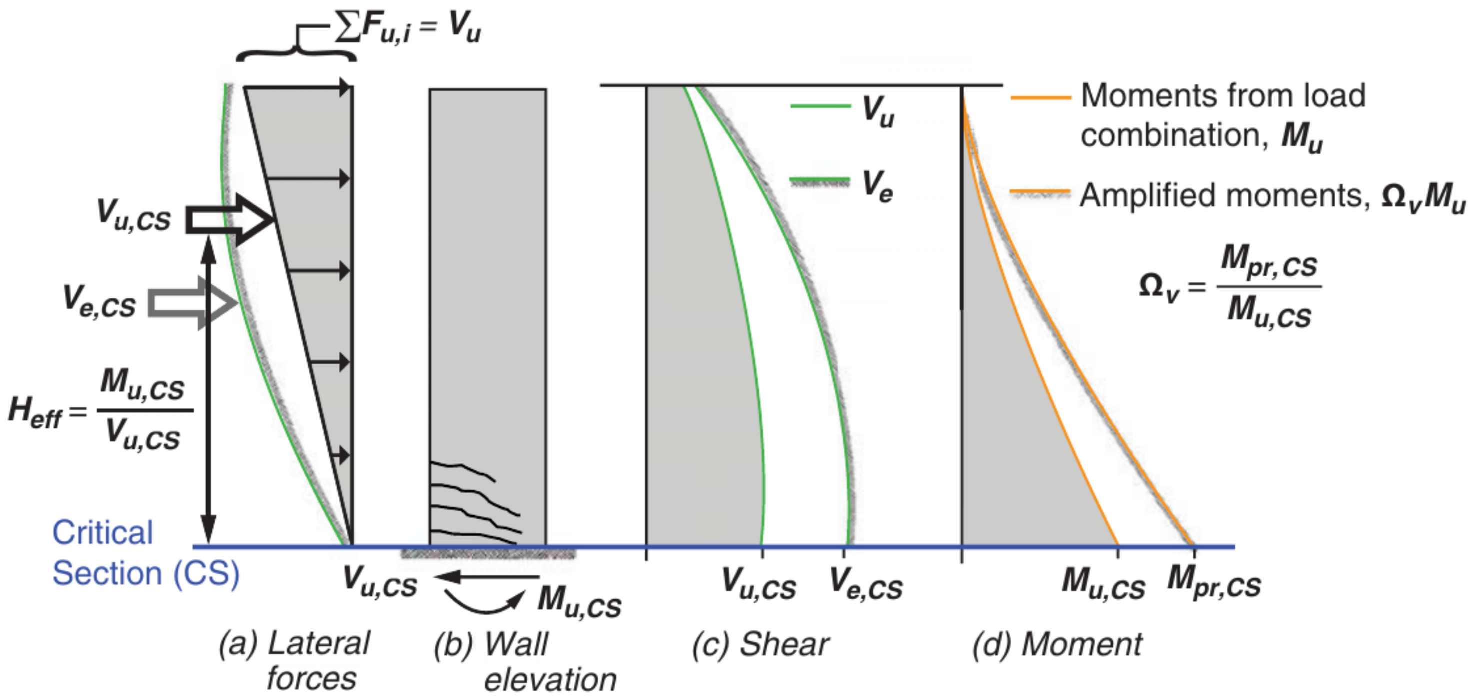




Concept of performance based seismic design/evaluation

Shear amplification effect in PBD

- In PBD of RC wall structures, shear force is significantly amplified during nonlinear analysis.
- Such shear amplification effect occurs by dynamic mode effects of slender shear walls.
- Thus, large amount of shear reinforcement is needed. → Increase in cost
- Shear strength of wall is needed to be estimated more accurately.



Shear force amplification effect (ACI 318-19)

Current shear strength model for RC walls

- In design codes, shear strength of walls is defined as $V_n = V_c + V_s$
- However, more design parameters should be addressed in strength model

Shear strength model of current design codes

Design code	Shear strength equations
ACI 318-19, Section 22.5 (one-way)	$V_c = \left(0.17\sqrt{f_c'} + \frac{N_u}{6A_g}\right) b_w d$ or $\left(0.66\rho^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right) b_w d$
	$V_c = \left(0.66\rho_w^{1/3}\lambda_s\sqrt{f_c'} + \frac{N_u}{6A_g}\right) b_w d$
ACI 318-19, Section 11.5.4.3 (wall)	$V_n = \left(\alpha_c\sqrt{f_c'} + \rho_h f_y\right) A_{cv} \le V_{nmax} = 2/3\sqrt{f_c'} A_{cv}$
KDS 14 20 22, Section 4.2 (one-way)	$V_c = \frac{1}{6}\sqrt{f_c'} b_w d, \quad V_s = A_v f_y d/s$
	$V_c = \frac{1}{6}\left(1 + \frac{N_u}{14A_g}\right)\sqrt{f_c'} b_w d$
KDS 14 20 22, Section 4.9.2 (wall)	$V_{c1} = 0.28\sqrt{f_c'} t_w d + \frac{N_u d}{4 l_w}$ $V_{c2} = \left[0.05\sqrt{f_c'} + \frac{l_w\left(0.1\sqrt{f_c'} + 0.2\frac{N_u}{4 l_w t_w}\right)}{\frac{M_u}{V_u} - \frac{l_w}{2}}\right] t_w d, \quad V_c = \min(V_{c1}, V_{c2})$
Eurocode 2	$V_{Rd,c} = \left[C_{Rd,c} k (100\rho_l f_c')^{1/3} + k_1\sigma_{cp}\right] t_w d$
	$V_{Rd,s} = \frac{A_{vh}}{s_h} z f_{ywd} \cot\theta$

Research purpose

- Shear strength model for RC walls is developed based on two shear mechanisms.

  1) Diagonal tension cracking: slender RC walls with light (or moderate) shear reinforcement

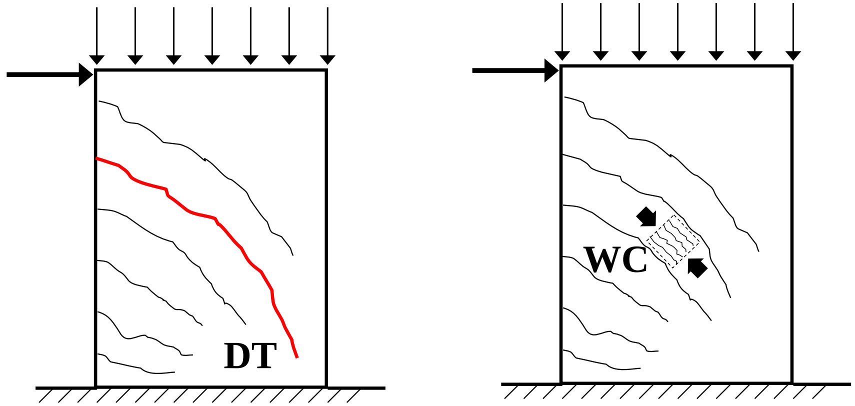
  2) Web crushing: slender RC walls with over shear reinforcement and high axial force

- Various design parameters can be addressed, and simplified model is suggested.

  1) Uniformly distributed web reinforcement

  2) Axial compression force

  3) Shape of wall cross-section (rectangle, T-shape, H-shape)



Diagonal tension cracking   Web crushing

Major shear failure mechanisms

Shear strength model

Strength degradation in RC walls

- The failure mode of a RC walls depends on the shear strength (Diagonal tension strength)

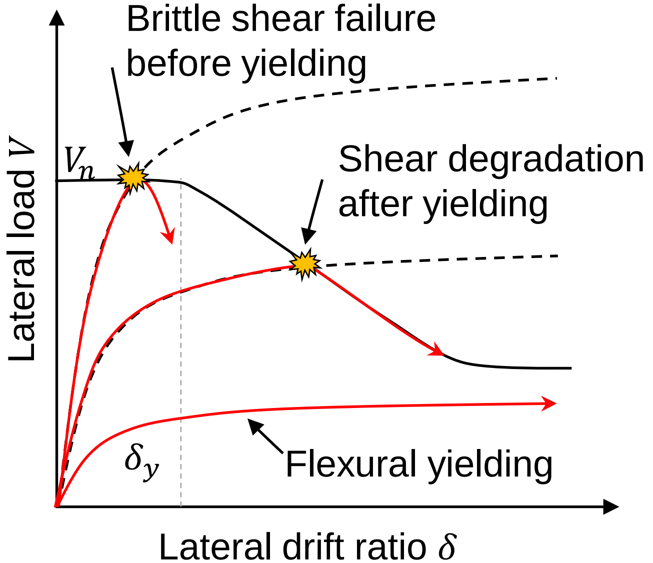
  1) In case of $V_f > V_n$: brittle shear failure mode → present study

  2) In case of $V_f < V_n$: flexural-shear failure mode

  3) In case of $V_f << V_n$: flexural yielding mode
- The shear strength is defined based on major shear failure mechanisms
- Diagonal tension cracking:

  - lightly reinforced wall, slender wall
- Web crushing

  - over-shear reinforced wall, heavy boundary element



Load-displacement relationships of RC walls affected by shear

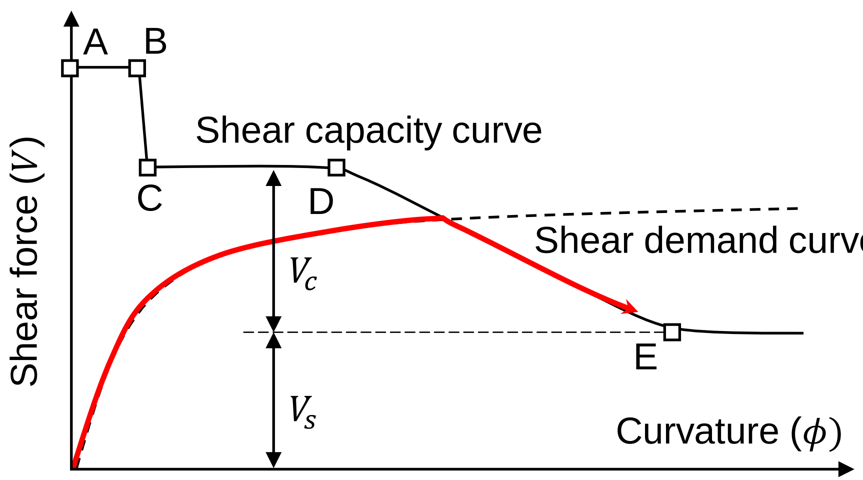
Diagonal tension cracking theory model (Compression zone failure mechanism, Choi, 2017)

- The shear resistance of a flexural member can be defined in the intact concrete.
- Shear stress capacity is defined based on Rankine's failure criteria
- The normal stress σ and the compression zone depth c vary according to flexural deformation.
- Thus, **the shear capacity varies according to the flexural deformation.**

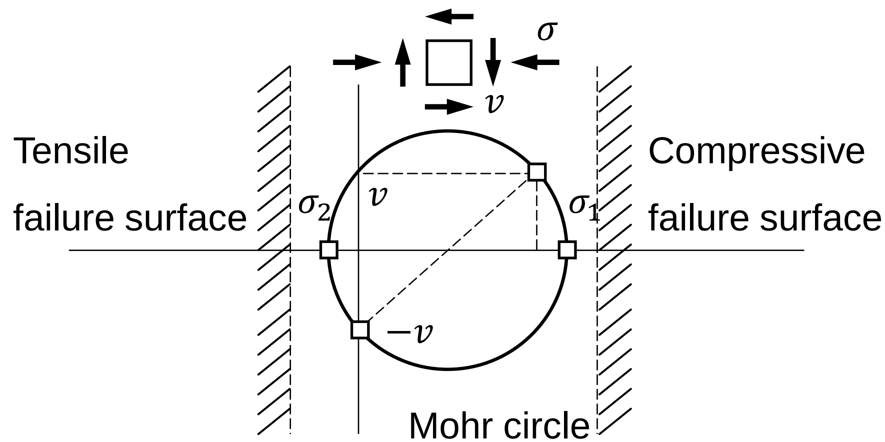
  - Stage AB : uncracked section

  - Stage CD : flexural cracking

  - Stage DE : concrete crushing



Shear capacity and demand curve



$$v_{cc}(z) = \sqrt{f_c'\left(f_c' - \sigma(z)\right)}$$ controlled by compression

$$v_{ct}(z) = \sqrt{f_t'\left(f_t' + \sigma(z)\right)}$$ controlled by tension

$$v_c(z) = \min\left(v_{cc}(z), v_{ct}(z)\right) \quad V_c = \int_0^c v_c(z)\,dz$$

Rankine's failure criteria and concrete shear capacity

Shear capacity defined by diagonal tension cracking

- For shear failure before flexural yielding, following assumptions are made

  i) Shear stress is governed by tension failure

  ii) Linear normal stress-strain distribution

- Nonlinear distribution of shear stress in comp. zone

  → Use equivalent stress block for simplification

  $$\rightarrow v_{c,eq} = \sqrt{f_t(f_t + \sigma_m)} = f_t\sqrt{1 + \sigma_{cm}/f_t}$$

- Thus, concrete shear strength

  1) rectangle wall

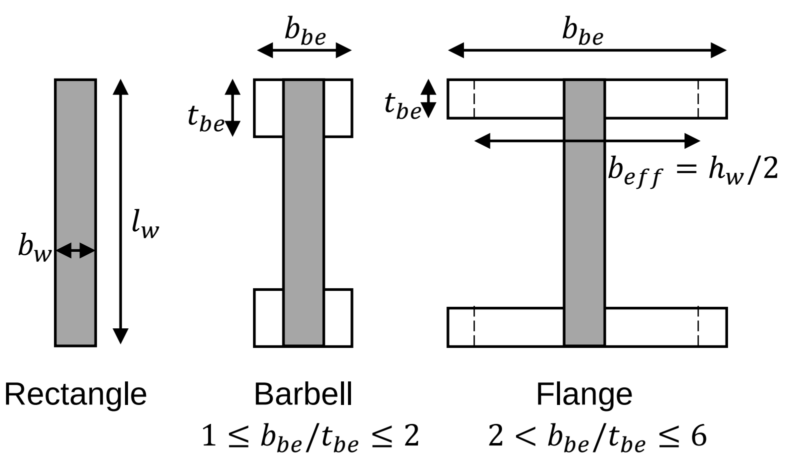
  $$V_c = v_{c,eq} c b_w = f_t\sqrt{1 + \sigma_{cm}/f_t}(cb_w)$$

  2) barbell shape or flanged wall

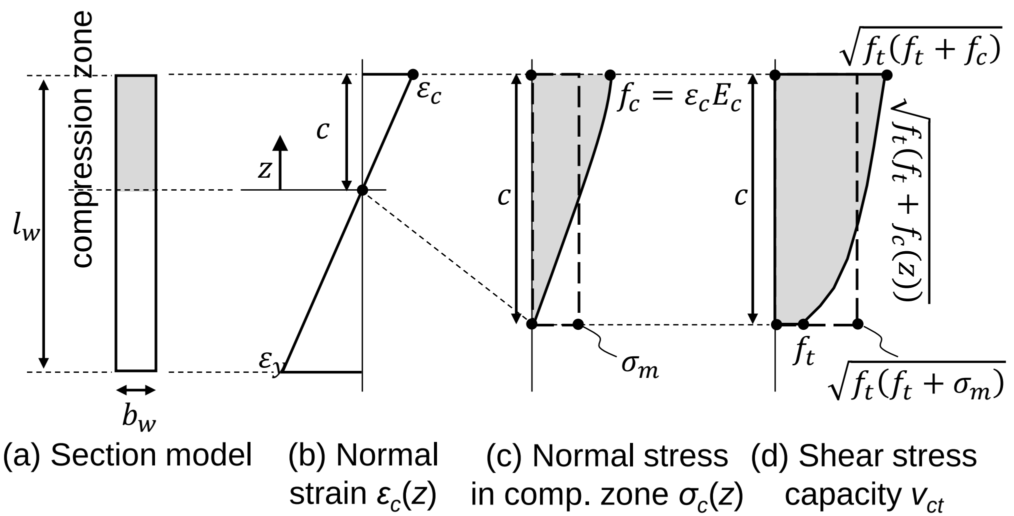
  $$V_c = v_{c,eq}\left[(c - t_{be})b_w + t_{be}b_{eff}\right]$$

  $$= f_t\sqrt{1 + \sigma_{cm}/f_t}(cb_w)$$

  $$+ f_t\sqrt{1 + \sigma_{cm}/f_t}\left(b_{eff} - b_w\right)t_{be}$$



Shape of wall cross-section



Shear stress in compression zone

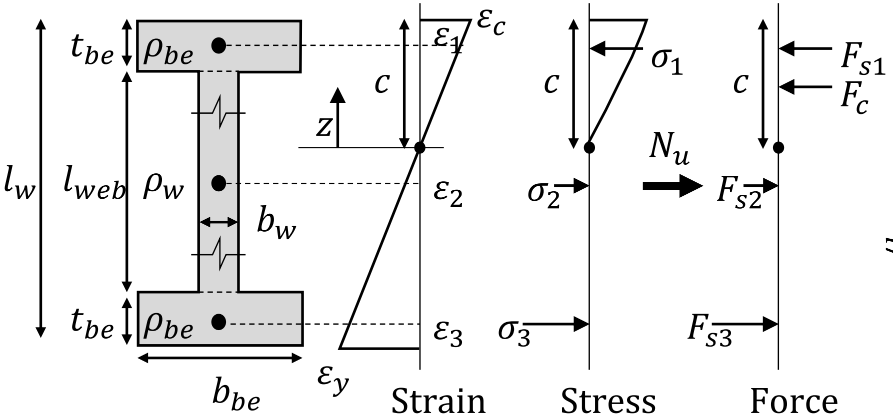
Shear capacity defined by diagonal tension cracking

- Using linear stress-strain relationship, previous Eqs. are simplified.
- Parameter: 1) Comp. zone ratio (c/l_w), 2) crack angle $(cot\ \phi)$
- Case i) For rectangular shape wall: $V_c = \alpha_1\sqrt{f_c}\, l_w b_w$
- Case ii) For barbell shape or flanged wall: $V_c = \alpha_1\sqrt{f_c}\, l_w b_w + \alpha_2\sqrt{f_c}(b_{be} - b_w)t_{be}$
- (c/l_w) : is suggested based on parametric analysis using simplified sectional analysis model

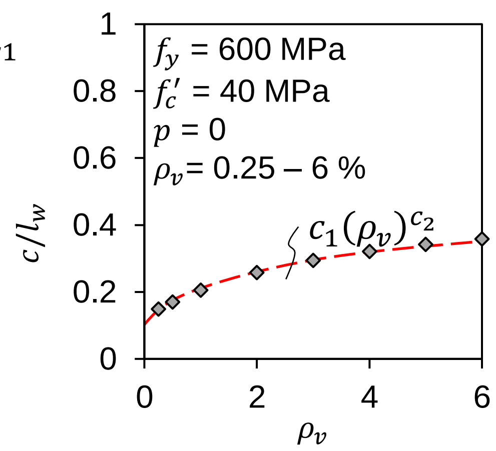
Where,
$\alpha_1 = 0.2 \cot\phi\,(c/l_w)$
$\alpha_2 = 0.2 \cot\phi$
$\cot\phi = \sqrt{1 + \sigma_{cm}/f_t}$

$$\boldsymbol{c/l_w = 0.89\left({\rho_v}^{1/3}\right) + 0.165p\sqrt{f'_c} \le 0.5}$$

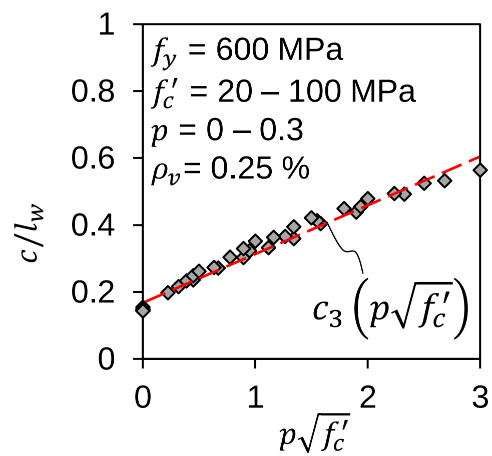
- $(\cot\phi)$: is suggested as $\phi = 15°$ based on parametric analysis results ($\phi = 10 - 20°$)



Simplified sectional analysis model



(a) Effect of V-rebar ratio



(b) Effect of axial load

Parametric analysis to determine parameters

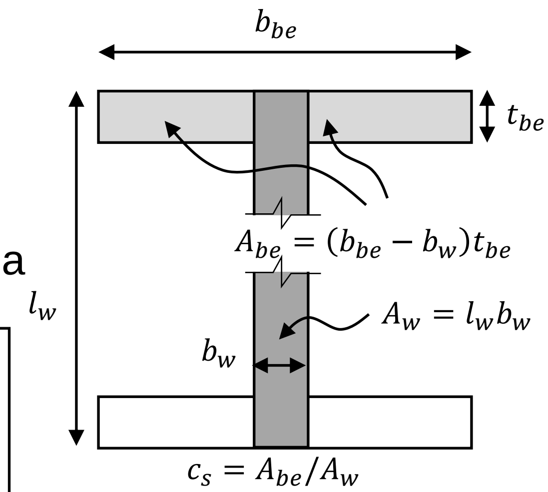
Shear capacity defined by diagonal tension cracking

- Thus, a simplified shear strength based on diagonal tension cracking is defined as follows:
- The characteristics of proposed model:

  1) Effect of compression zone depth on shear strength

  is expressed by ρ_v, f_c', N_u

  2) Effect of flange wall is addressed by increase of comp. zone area



- The proposed model is similar to ACI 318-19 one-way shear model

cf) ACI 318-19 (one-way)

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

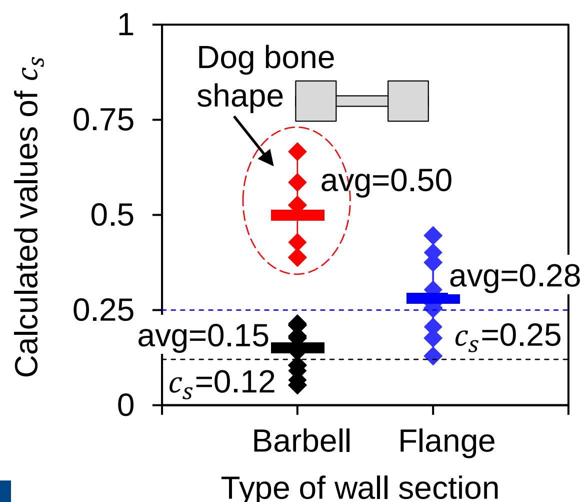
- Case i) For rectangular shape wall:

$$V_c = 0.2\cot\phi\,(c/l_w)\sqrt{f_c'}\,l_w b_w = \left(0.66{\rho_v}^{1/3}\sqrt{f_c'} + \frac{N_u}{8A_g}\right)A_{cv}$$

- Case ii) For barbell shape or flanged wall:

$$V_c = 0.2\cot\phi\,(c/l_w)\sqrt{f_c'}\,l_w b_w + 0.2\cot\phi\sqrt{f_c'}(b_{be} - b_w)t_{be}$$

$$= \left((0.66{\rho_v}^{1/3} + 0.75c_s)\sqrt{f_c'} + \frac{N_u}{8A_g}\right)A_{cv}$$



Definition of c_s

Web crushing theory model (Truss mechanism model, Eom, 2013)

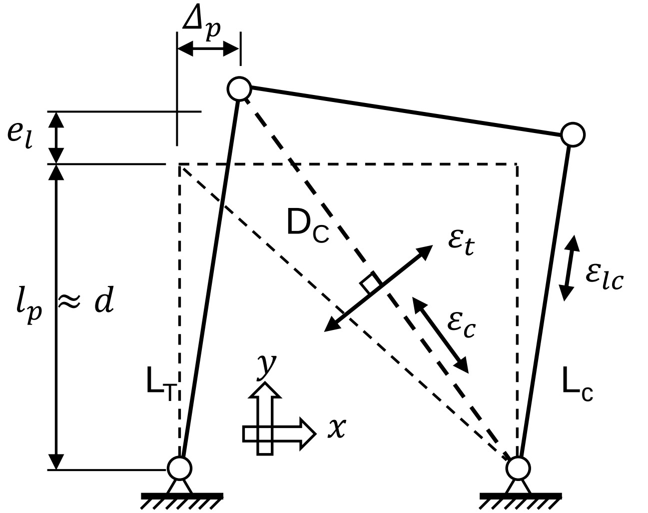
- In the over-reinforced RC walls, shear capacity is governed by thin web concrete.
- Web crushing strength defined by diagonal concrete strut strength:

$$V_{wc} = f_{ce} l_{web} b_w \cos\theta \sin\theta$$

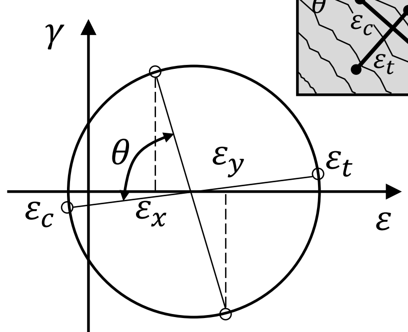
- Effective concrete strut stress:

$$f_{ce} = \left(\frac{f_c'}{0.8+0.34(\varepsilon_t/\varepsilon_{co})}\right) \le f_c' \text{ (Vecchio and Collins 1986)}$$

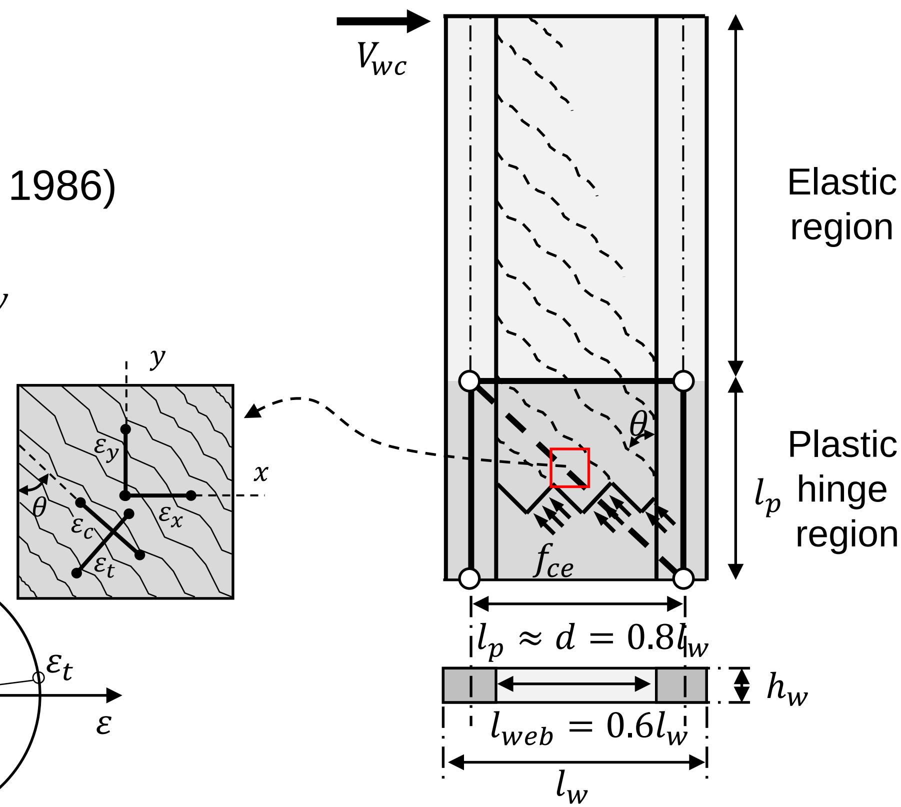
where, ε_t =principal tensile strain = $\varepsilon_c + \varepsilon_x + \varepsilon_y$



Strain of truss elements



Strain Mohr's circle



Shear transfer of web concrete with inclined cracking: truss analogy

Shear capacity defined by web crushing

- In previous principal strain, each strain is defined as follows:

  1) Principal compressive strain $\varepsilon_c = \varepsilon_{co}$: concrete compressive strain at flexural yielding

  2) Horizontal strain $\varepsilon_x \approx \varepsilon_{yh}$: average strain within diagonal cracking

  3) Vertical strain $\varepsilon_y = e_l/l_p$: average strain based on vertical elongation → but zero

- Effective compressive strength of diagonal strut

$$f_{ce} = \frac{f_c'}{1.14 + 0.34\left(f_{yh}/400\right)}$$

- Web crushing strength (Maximum shear strength)

$$V_{wcm} = \beta_c f_c' l_w b_w$$

$$\beta_c = \frac{1}{3.8 + 1.13\left(f_{yh}/400\right)} \approx \begin{cases} 1/5 & \text{For } f_{yh} \leq 400 \text{ MPa} \\ 1/6 & \text{For } f_{yh} \geq 800 \text{ MPa} \end{cases}$$

cf) Eurocode maximum shear strength :

when, $f_c' < 60$ MPa, $\alpha_{cw} = 1.0$, $v_1 = 0.6$, z = 0.8*d*, $\theta = 45°$

$$V_{Rd,max} = \alpha_{cw} v_1 f_c' h_w z(\tan\theta + \cot\theta) = 0.19 f_c' h_w l_w$$

Model verification

Model verification

ρ_v = Average reinf. ratio
N_u = Axial load
A_g = Total area

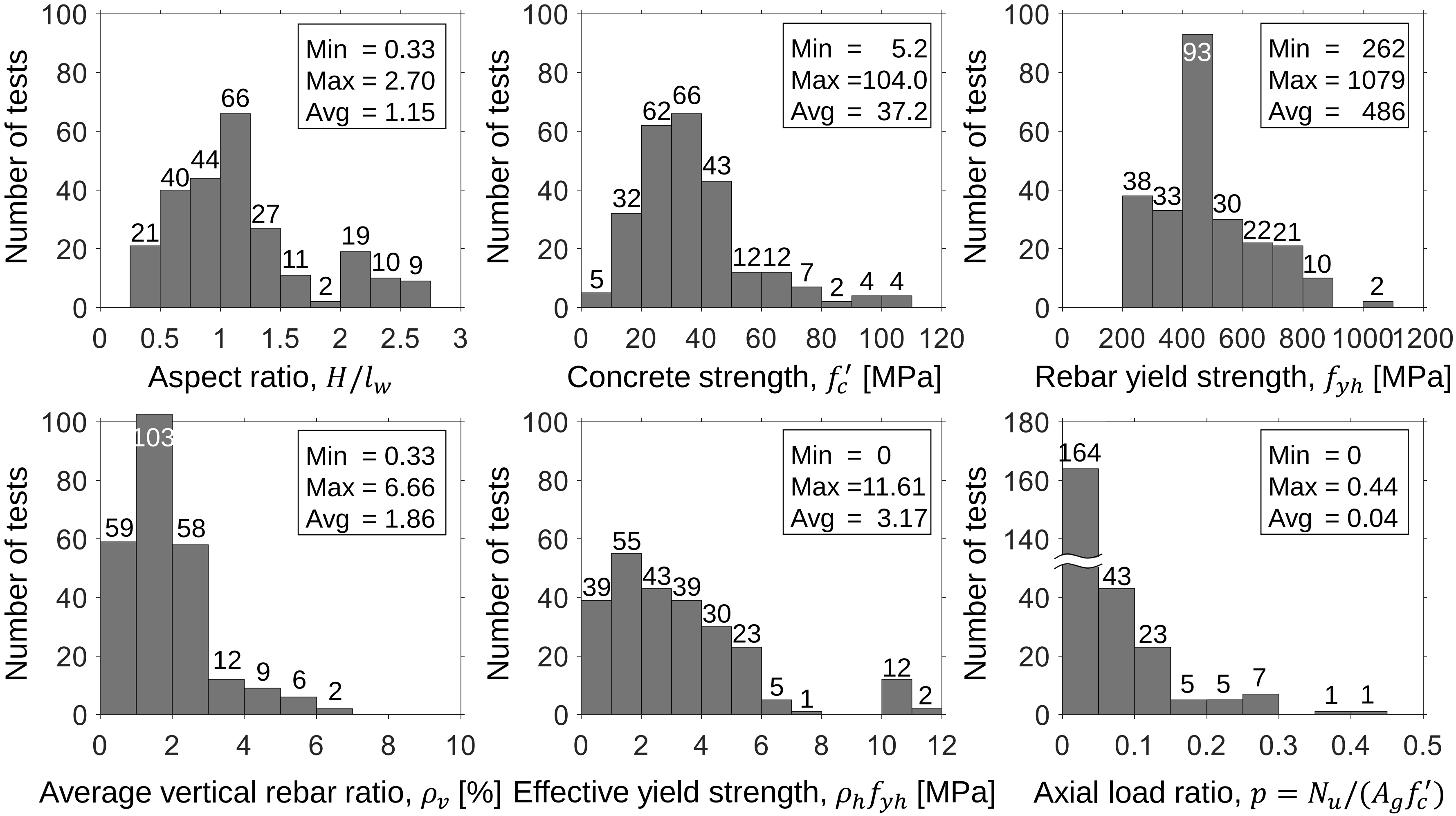
$c_s = 0$ For rectangle wall
$c_s = 0.12$ For barbell wall
$c_s = 0.25$ For flanged wall

$$\beta_c = \begin{cases} 1/5 \text{ For } f_{yh} \le 400 \text{ MPa} \\ 1/6 \text{ For } f_{yh} \ge 800 \text{ MPa} \end{cases}$$

Existing RC wall tests database

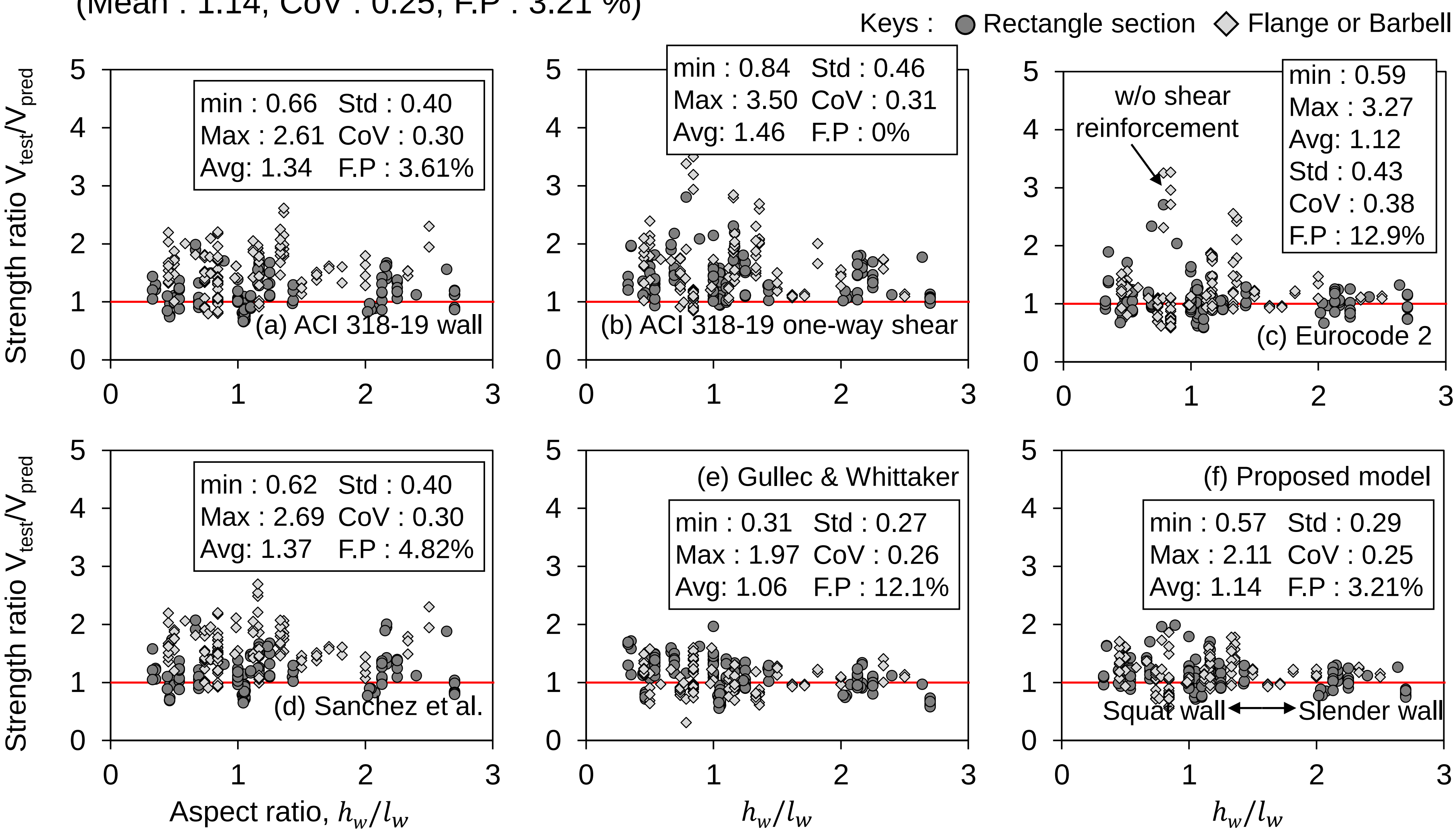
- Overall 249 wall test specimens

$$V_n = V_c + V_s = \left((0.66{\rho_v}^{1/3} + 0.75c_s)\sqrt{f_c} + \frac{N_u}{8A_g} + \rho_h f_{yh} \right) l_w b_w \le V_{wcm} = \beta_c f_c' l_w b_w$$



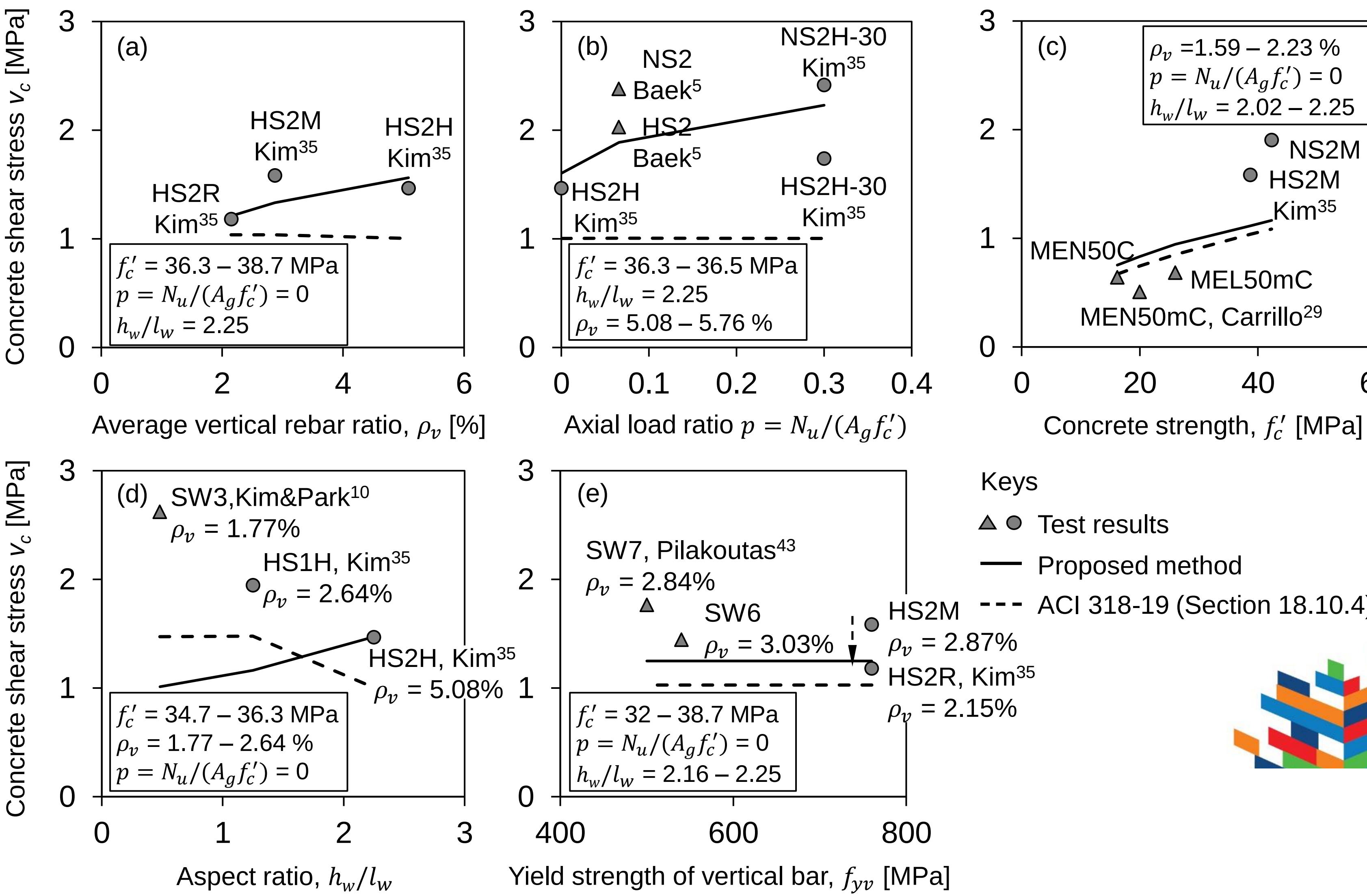
Shear strength predictions

- The proposed model has better accuracy compared to other strength model (Mean : 1.14, CoV : 0.25, F.P : 3.21 %)



Effect of design parameters on shear strength

- The proposed model address the effects of design parameters on shear strength reasonably.



Conclusions

Summary

- The present study developed **a simplified shear strength model** of RC walls
- Based on the failure mechanisms, the shear strength degradation was defined

  1) Diagonal tension cracking : **effective shear resistance in uncracked compression zone**

  2) Web crushing : **effective strength of diagonal concrete strut in web**
- Additionally, the design characteristics of walls are addressed:

  1) **uniformly distributed vertical reinforcement**

  2) **axial compression force**

  3) **wall cross-sectional shape**
- For verification, the proposed models were applied to the existing test results.
- The proposed model agreed with test results, and captured the effect of parameters.

- ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (318R-19)”, American Concrete Institute, Farmington Hills, MI, 2019.
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- Choi, K-K, and Park, H-G, “Evaluation of inelastic deformation capacity of beams subjected to cyclic loading”, ACI Structural Journal, V. 107, No. 5, Sept.-Oct. 2010. pp. 507-515.
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Thank you for listening

Contact: wizkim@ssu.ac.kr

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