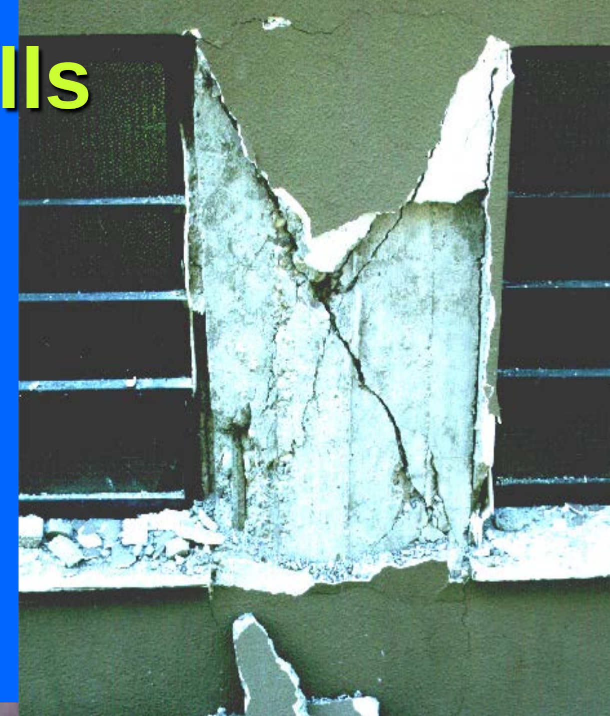
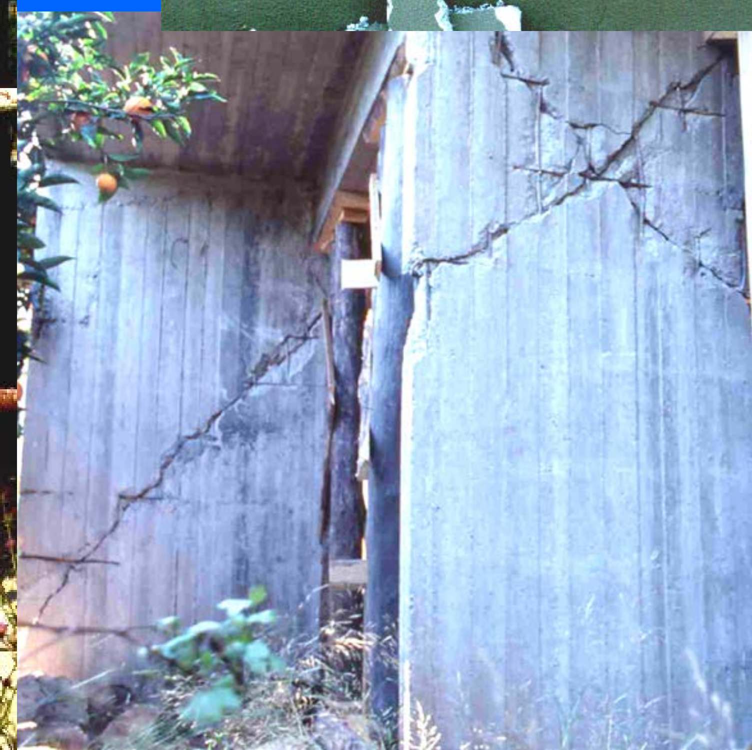
BEHAVIOUR OF CONCRETE MEMBERS UNDER CYCLIC LOADING

II. CONCRETE MEMBERS

Shear
(w/ some effects of inelastic flexure)

Shear failures of columns or walls

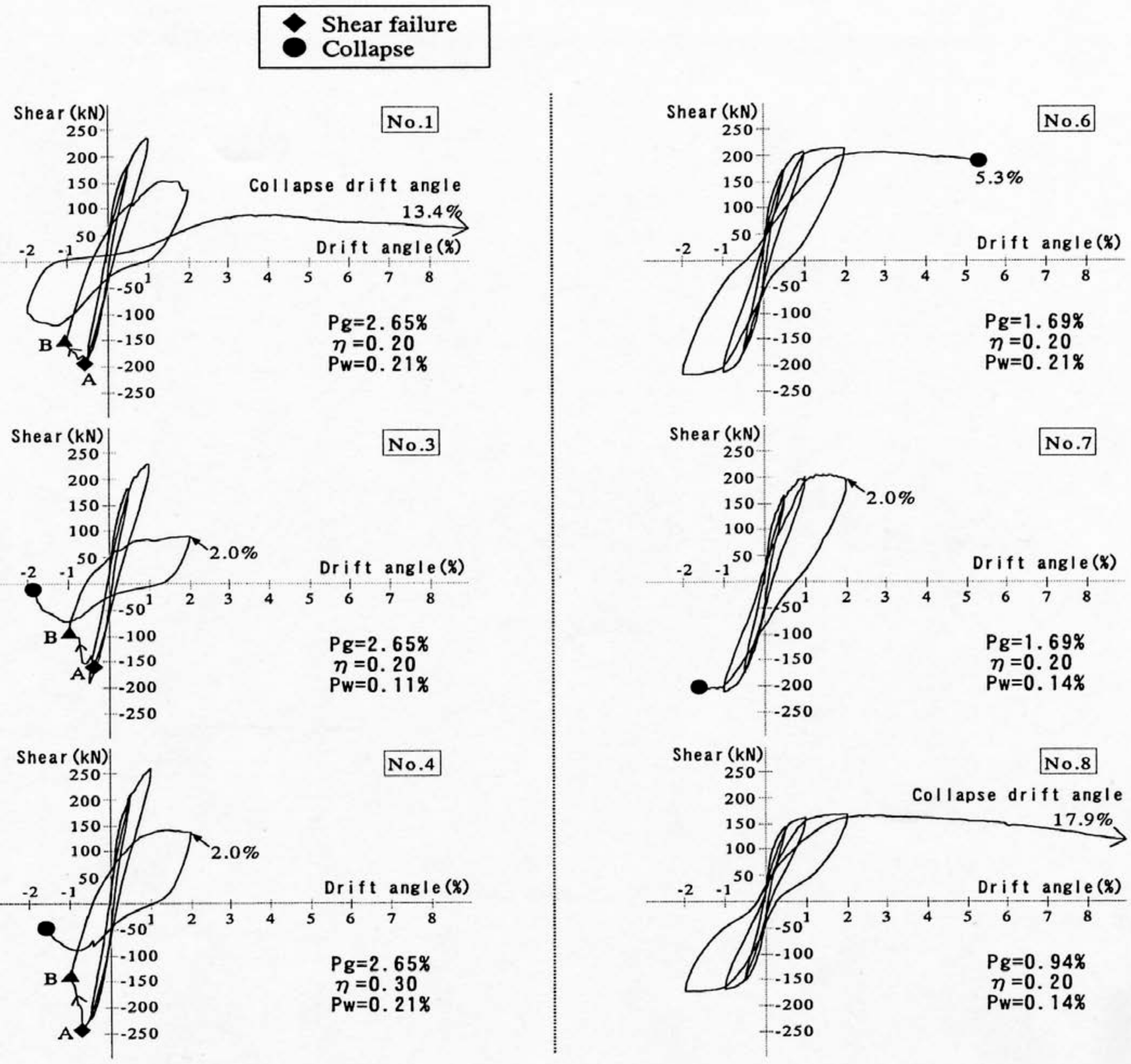




Shear failures of columns or walls

(top two, in plastic hinge region)

Brittle vs ductile behaviour in cyclic shear



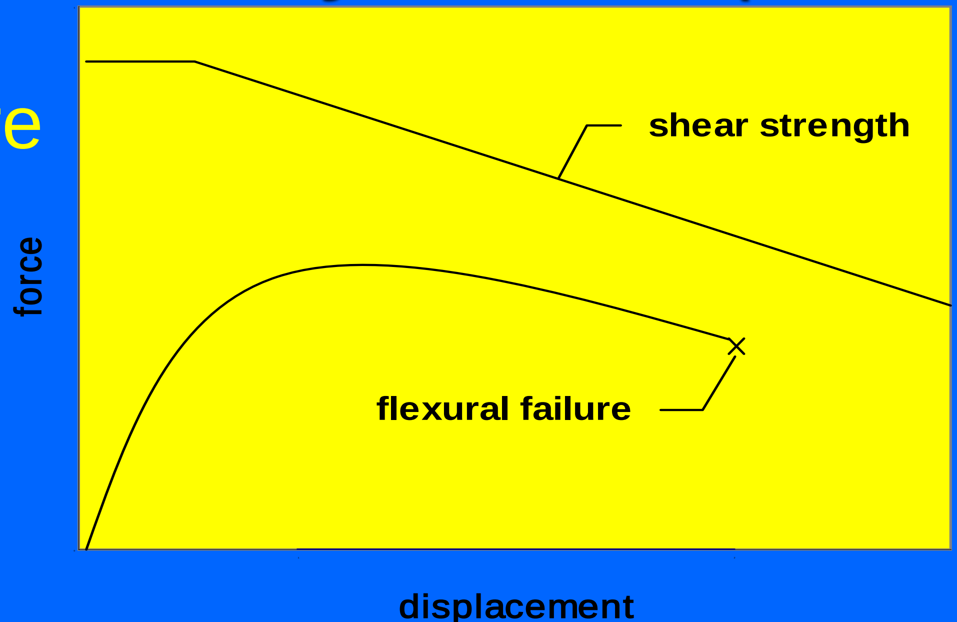
(a) Shear mode

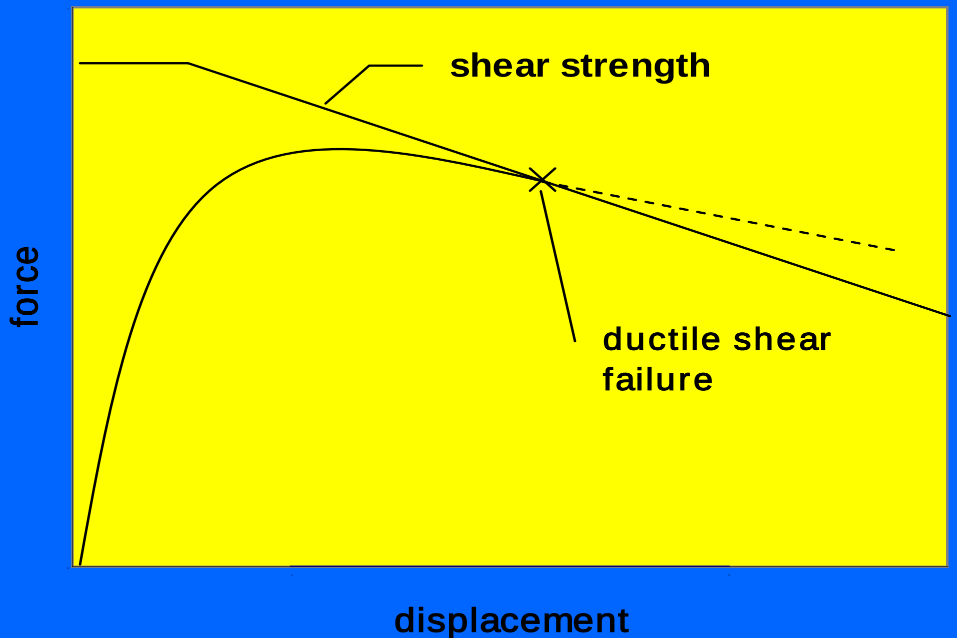
(b) Flexure-Shear mode
(No.8: Flexure mode)

Shear force-chord rotation behaviour:
(a) brittle shear;
(b) “ductile shear” or flexural behaviour

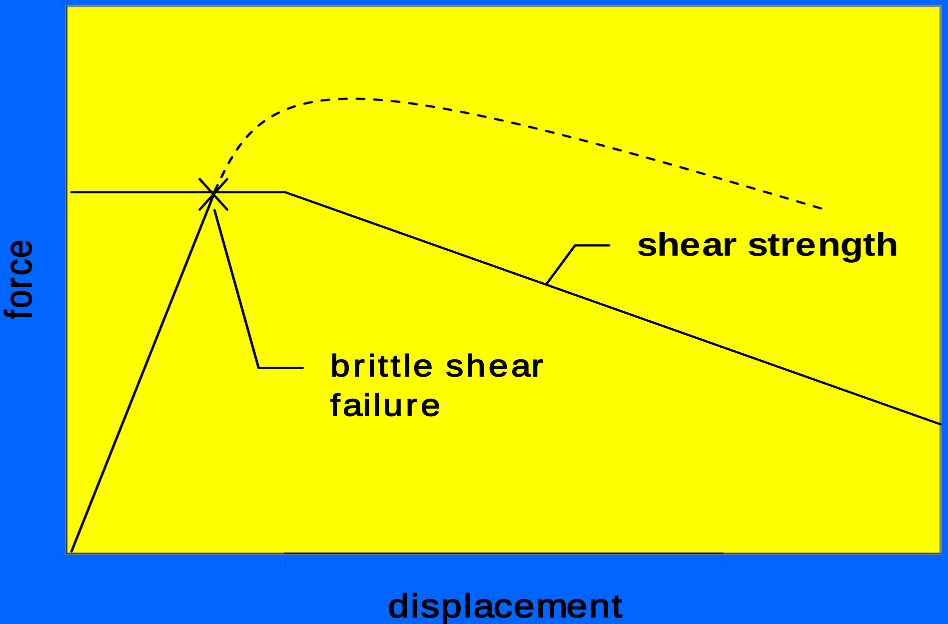
Brittle vs ductile behaviour in cyclic shear (cont'd)

Flexural failure



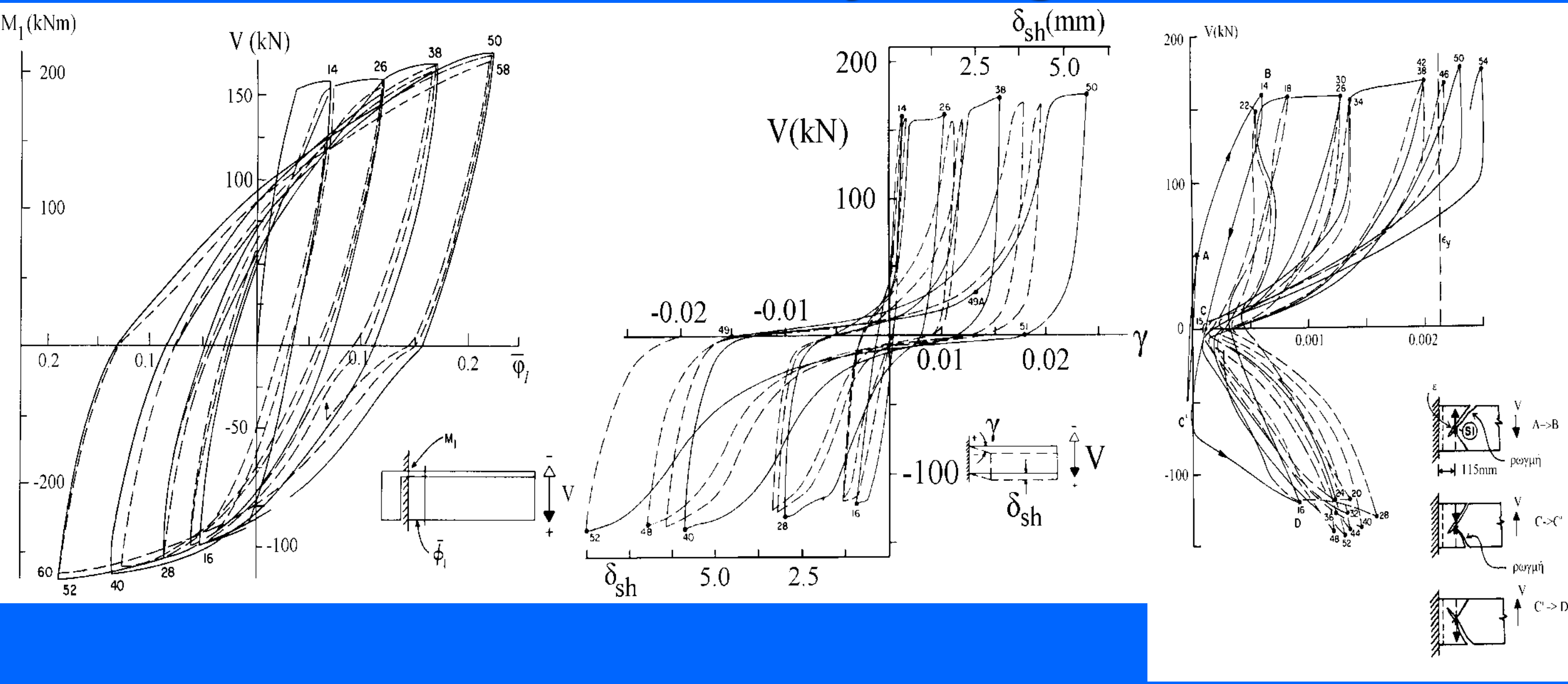


Ductile shear failure



Brittle shear failure

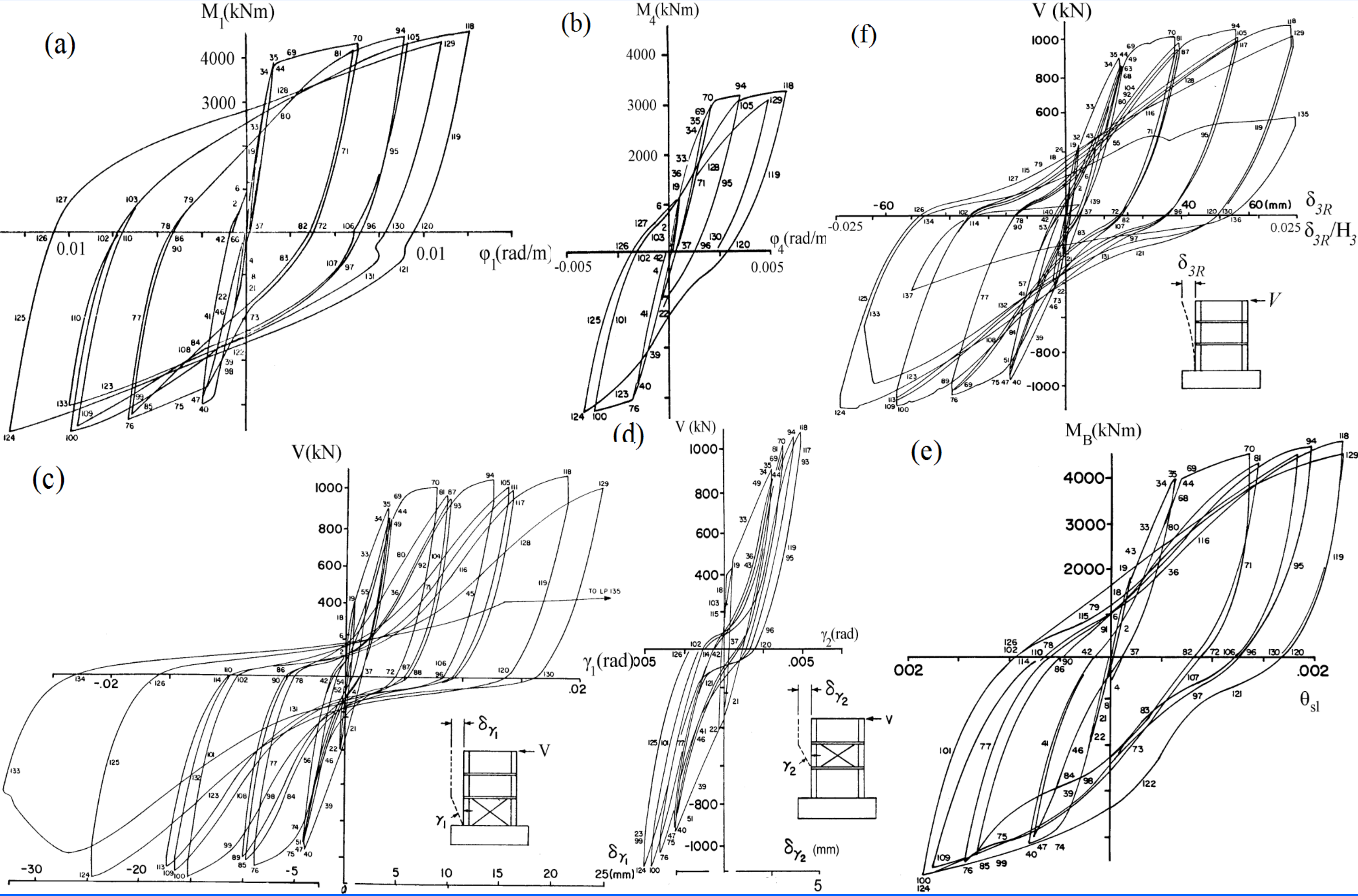
Effect of cyclic inelastic deformations on shear behaviour after flexural yielding



(a) (b) (c)

(a) *M*-*φ* loops next to end section; (b) *V*-*γ* loops in plastic hinge region; (c) loops of shear force (V) - stirrup strain

Effect of cyclic inelastic flexural deformations on shear behaviour -cont'd



(a), (b): *M*-*φ* loops next to base of 1st & 2nd storey; (c), (d): *V*-*γ* loops over 1st & 2nd storey; (f) base shear v top deflection (e) loops of base moment v fixed-end rotation due to bar pull-out from footing

Fundamental models - monotonic shear resistance

Truss model w/ variable strut inclination δ, CEB/FIP Model Code 90 & Eurocode 2

– Shear resistance in diagonal tension,
due to transverse reinforcement: $V_R = \rho_w f_{yw} b_w z \cot\delta + 0.5N(h-x)/L_s$

- Eurocode 2: 0.4≤tanδ≤1, 22º≤δ≤45º,
  Model Code 90: 1/3≤tanδ≤1, 18º≤δ≤45º

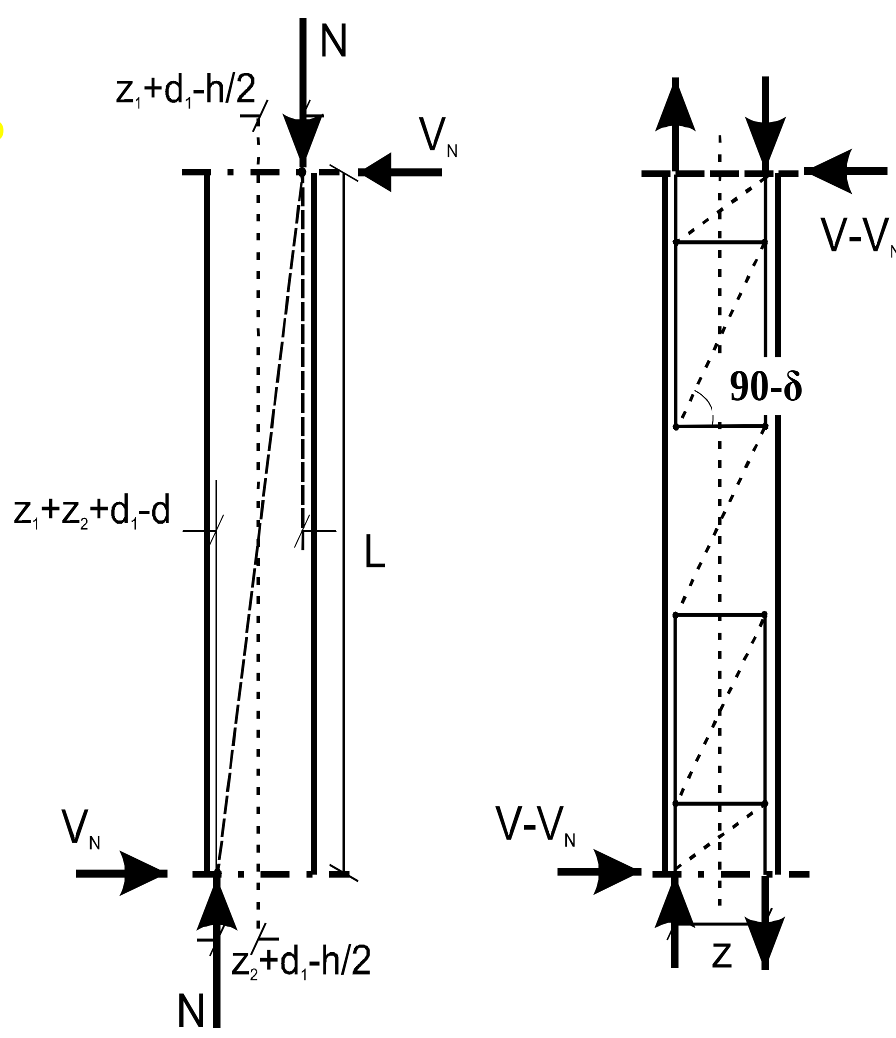
– Diagonal compression field at angle δ to member axis

$$= \rho_w f_{yw}(1+\cot^2\delta) < nf_c$$

– may reach diagonal concrete strength, nf_c

– *n:* reduction factor due to transverse tensile stresses/strains

- Eurocode 2 & Model Code 90:
  n=0.6(1-f_c(MPa)/250)



Fundamental models for monotonic shear resistance (cont'd)

AIJ Guidelines model

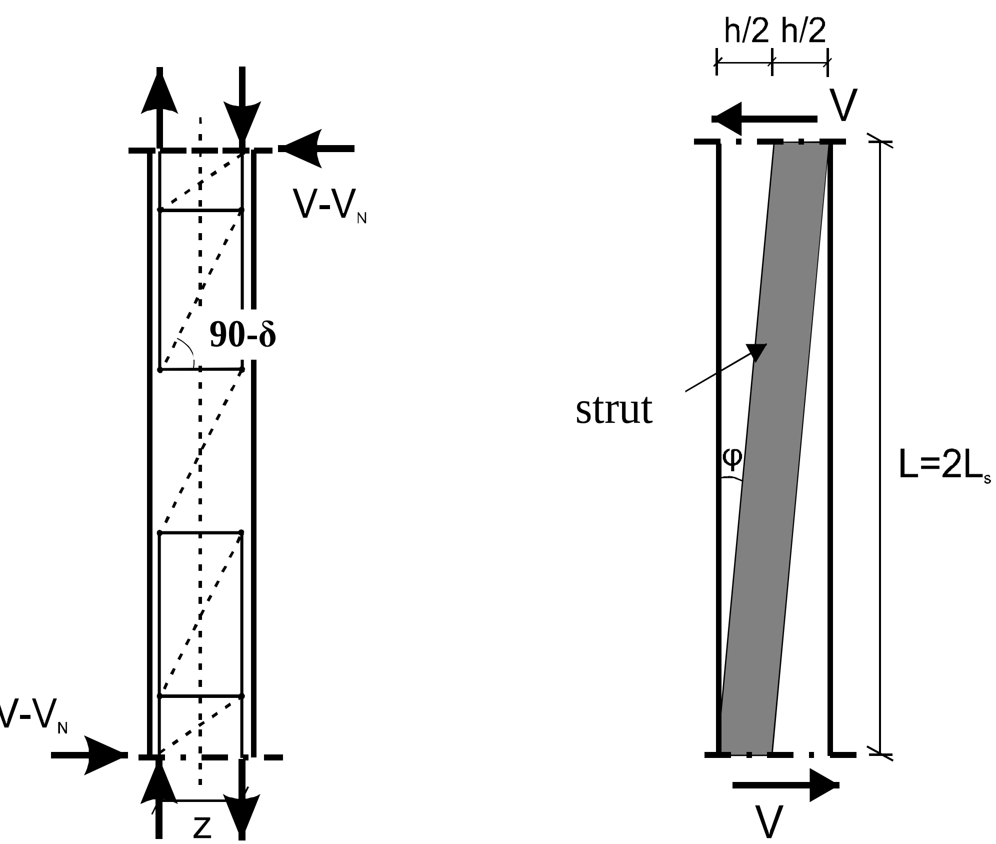
Concrete strut w/ width equal to 50% of section depth:

– contributes to V_R via transverse component of strut force;

– consumes part of the diagonal concrete strength, nf_c

– rest of concrete strength is available for diagonal compression field in truss mechanism (angle: δ)

$$V_R = \rho_w f_{yw} b_w z \cot\delta + 0.5 b_w h [n f_c - \rho_w f_{yw}(1+\cot^2\delta)]\tan\varphi$$



V_R for $\cot\delta \leq \min[2; \sqrt{(nf_c/\rho_w f_{yw}-1)}]$

unless: $0.5\tan\varphi$ ($\approx h/2L_s = h/L$) $\geq 2z/h$

Then V_R reaches maximum value if:

$\cot\delta = z/(h\tan\varphi) \approx 4L_s z/h^2$

Maximum V_R equal to (with $\zeta = z/h$):

$$V_R = 0.5 b_w h [n f_c \tan\phi + \rho_w f_{yw}(\zeta^2 - \tan^2\phi)]$$

Inelastic cyclic deformation effect:

- $\cot\delta \leq \max(2-50\theta_{pl}, 1)$;
- n on f_c multiplied x $\max(0.25, 1-15\theta_{pl})$

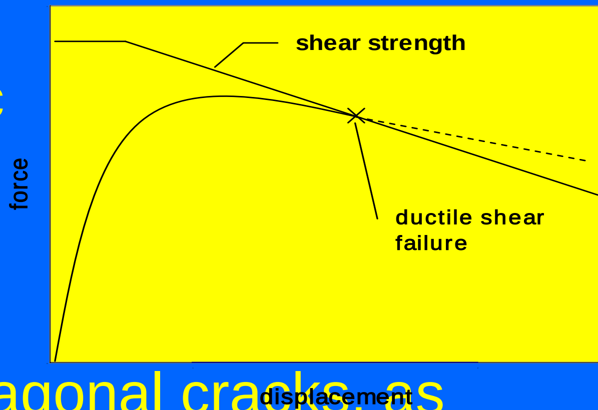
with $\theta_{pl} = (\mu_\theta - 1)\theta_y$

Cyclic shear strength degradation

– Shear resistance degrades with cyclic loading: RC member that yields in flexure may ultimately fail in shear.

– Provisions of concrete design codes for shear strength apply to monotonic loading;

– Seismic codes (e.g. EC8) may reduce V_R if cyclic ductility demands are high.



Degradation mechanisms :

• Gradual reduction of aggregate interlock along diagonal cracks, as interfaces become smoother with cyclic loading.

• Degradation of dowel action (also due to accumulation of inelastic strains in longitudinal reinforcement).

• Development of flexural cracks throughout the depth of the member → reduction of contribution of compression zone to shear resistance.

• Bond slippage & accumulation of inelastic strains in shear reinforcement → aggregate interlock reduced as diagonal cracks gradually open up.

• Softening of concrete in diagonal compression due to accumulation of transverse tensile strains.

Models for diagonal tension cyclic shear resistance after flexural yielding

Biskinis et al 2004, Part 3 of EC8 (circular columns, rectangular beams/columns/walls, non-rectangular walls, hollow rectangular piers)

$$V_R = \frac{h-x}{2L_s}\min\left(N,\,0.55A_c f_c\right)+0.16\cdot\left(1-0.095\min\left(5,\,\mu_\theta^{pl}\right)\right)\max(0.5,\,100\rho_{tot})\left(1-0.16\min\left(5,\frac{L_s}{h}\right)\right)\sqrt{f_c}A_c+V_w$$

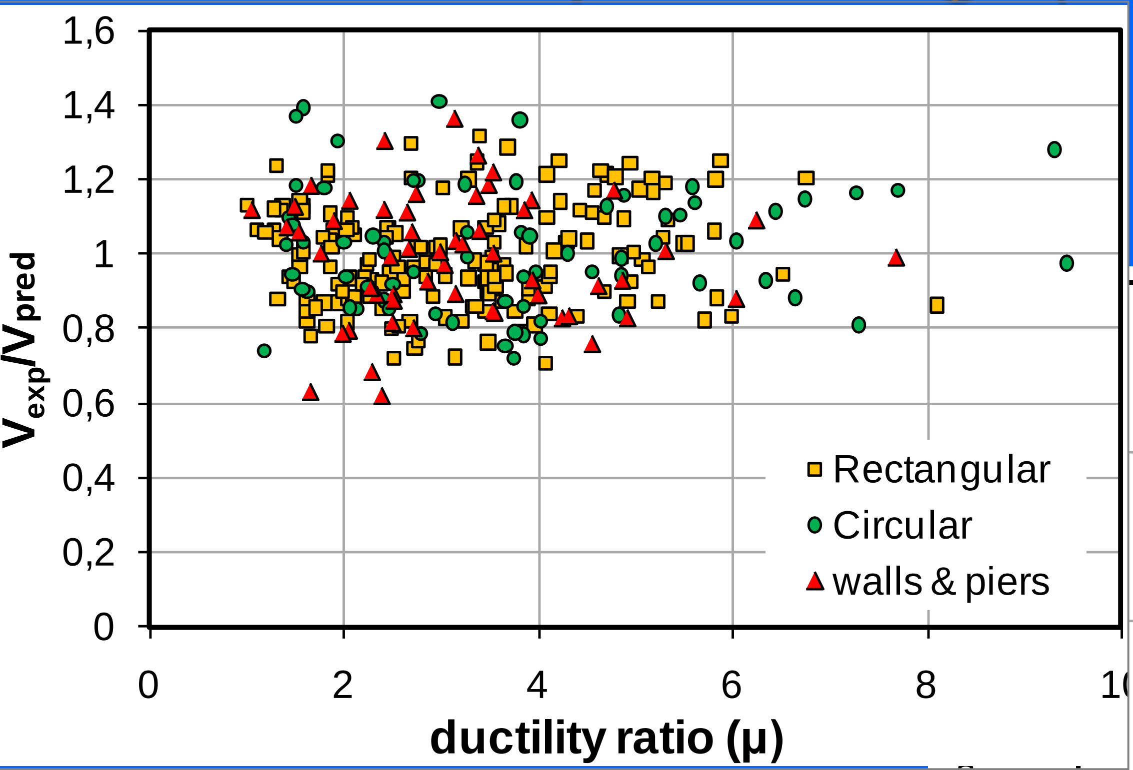
or:

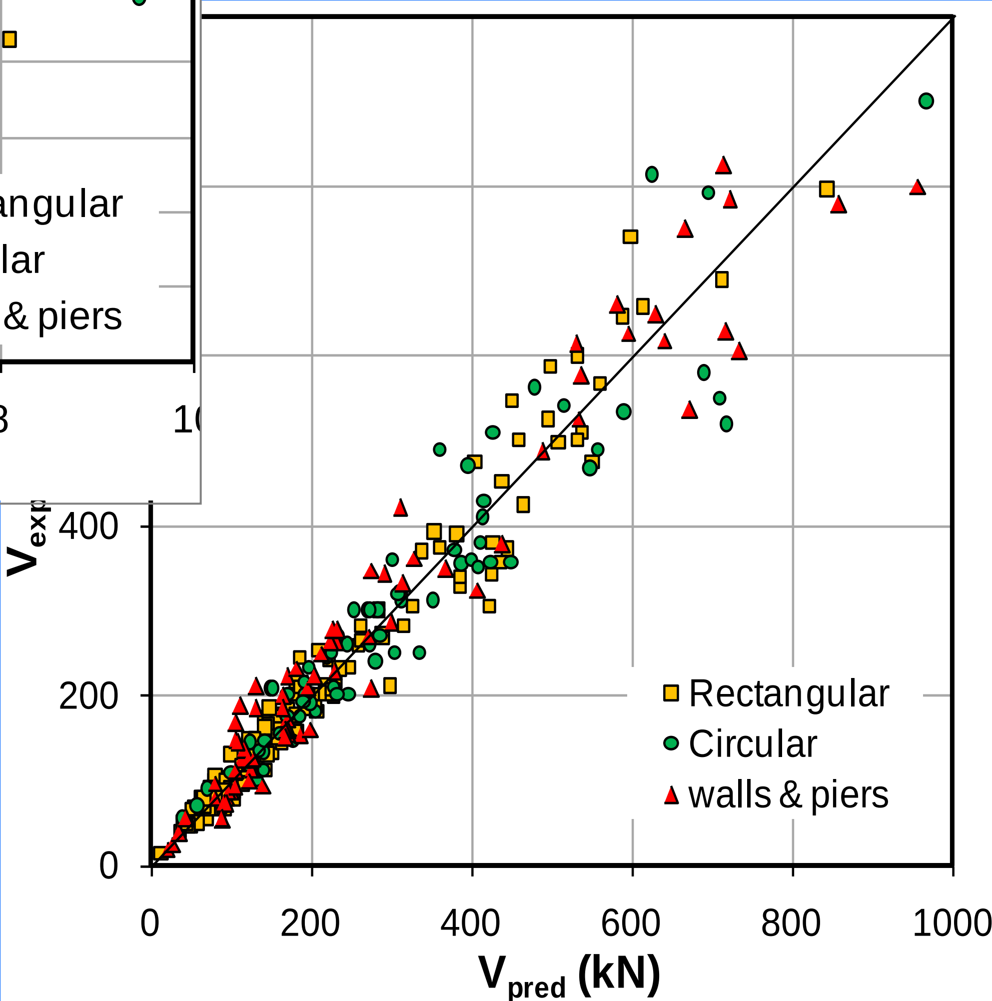
$$V_R = \frac{h-x}{2L_s}\min\left(N,\,0.55A_c f_c\right)+\left(1-0.05\min\left(5,\,\mu_\theta^{pl}\right)\right)\left[0.16\max(0.5,100\rho_{tot})\left(1-0.16\min\left(5,\frac{L_s}{h}\right)\right)\sqrt{f_c}A_c+V_w\right]$$

- V_w , V_N , V_c terms;
- Inclination of compression struts: δ =45° $\quad V_w = \rho_w b_w z f_{yw}$

- Linear degradation of V_c for ductility ratio demand from 1 to 6;
- In 1st model: V_c for $\mu_\theta \geq 6$ is 52.5% of initial one
- In 2nd model: V_w+V_c for $\mu_\theta \geq 6$ is 75% of initial one.

Test v model: Diagonal tension cyclic shear resistance in plastic hinge (after flexural yielding)





no. tests: 335
median=1.00
CoV=16.2%

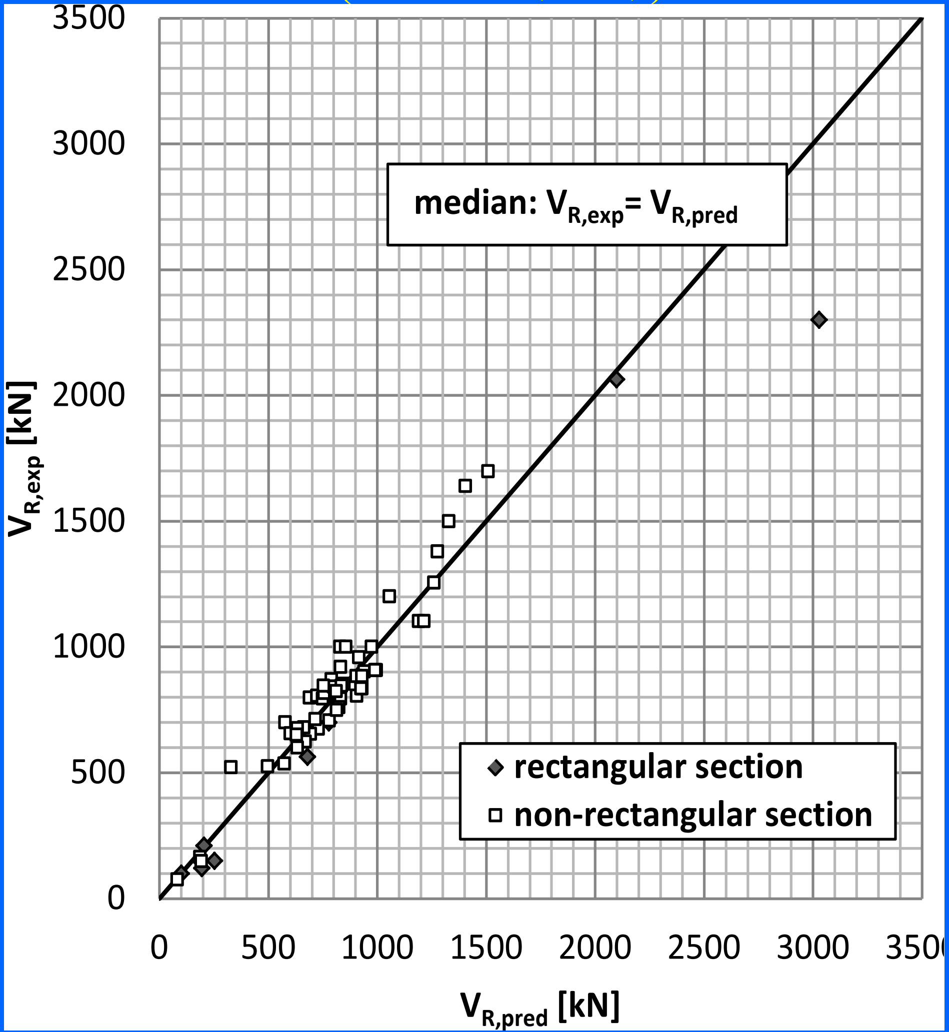
Cyclic shear resistance of squat walls in diagonal compression before or after flexural yielding

$$V_{R,\max} =$$

$$0.85\left(1-0.06\min\left(5;\mu_\theta^{pl}\right)\right)\left(1+1.8\min\left(0.15,\frac{N}{A_c f_c}\right)\right)\left(1+0.25\max\left(1.75;100\rho_{tot}\right)\right)\left(1-0.2\min\left(2;\frac{L_s}{h}\right)\right)\sqrt{\min\left(f_c;100\right)}b_w z$$

no. tests: 62, median=1.00, CoV=14.5%

Experimental cyclic shear resistance for shear compression failure of squat walls v predictions



Flexure-shear interaction in squat members

Monotonic lateral force resistance of squat members w/ flexure-shear interaction

Generalization of AIJ Guidelines model

Concrete strut over depth x of compression zone:

– takes also the axial load, N;

– contributes to V_R via transverse component of strut force;

– consumes part of diagonal concrete strength, nf_c

– rest of concrete strength is available for diagonal compression field in truss mechanism, at angle δ, w/ $\cot\delta \leq \sqrt{(nf_c/\rho_w f_{yw}-1)}$; $\cot\delta \sim L_s/h$.

Monotonic lateral force resistance of squat members w/ flexure-shear interaction (cont'd)

1. In axial force range: $N_1 = 0.5bhnf_c - A_{s,tot}f_y + \rho_w b_w f_{yw}\,[\cot\delta(2L_s + (z-0.5h)\cot\delta) - 0.5h] \leq$

$\boldsymbol{N} \leq N_2 = 0.5bhnf_c + A_{s,tot}f_y - \rho_w b_w f_{yw}\,[\cot\delta(2L_{s-(}z-0.5h)\cot\delta) + 0.5h]$

Strut inclination is:

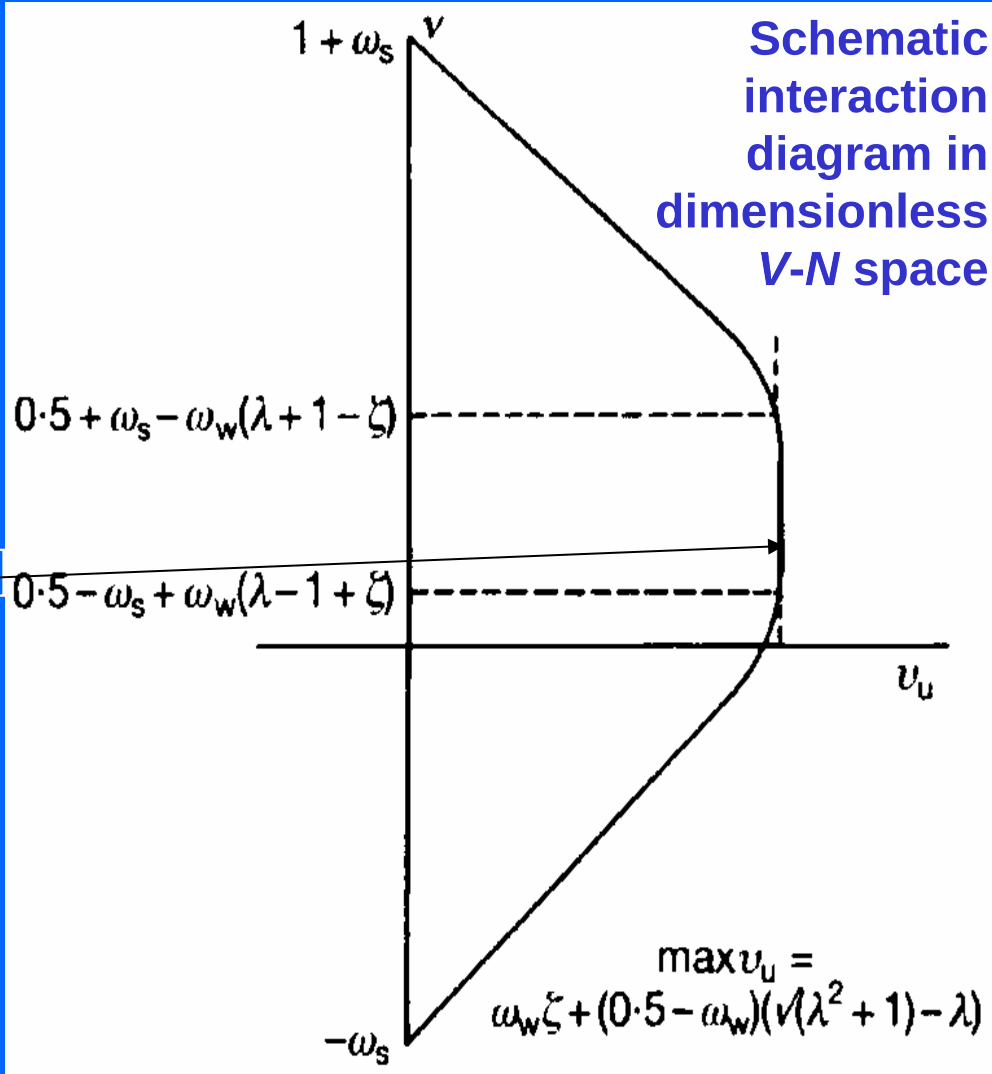
$$\tan\phi = \sqrt{\left(\frac{2L_s}{h}\right)^2 + 1} - \frac{2L_s}{h}$$

<u>Very brittle failure:</u>

Concrete fails in diagonal compression, w/ yielding of transverse reinforcement, but no yielding of tension or compression reinforcement, at an ultimate shear force of:

$$V_R = 0.5b_w h[nf_c \tan\phi + \rho_w f_{yw}(\zeta^2 - \tan^2\phi)]$$

N-range exists if: $$\cot\delta \leq \frac{\omega_{tot}}{\omega_w}\frac{h}{2L_s}$$



Schematic interaction diagram in dimensionless *V*-*N* space

Monotonic lateral force resistance of squat members w/ flexure-shear interaction (cont'd)

2. In axial force range: $N_1 \geq \boldsymbol{N} \geq -A_{s,tot}f_y$

Strut inclination is:

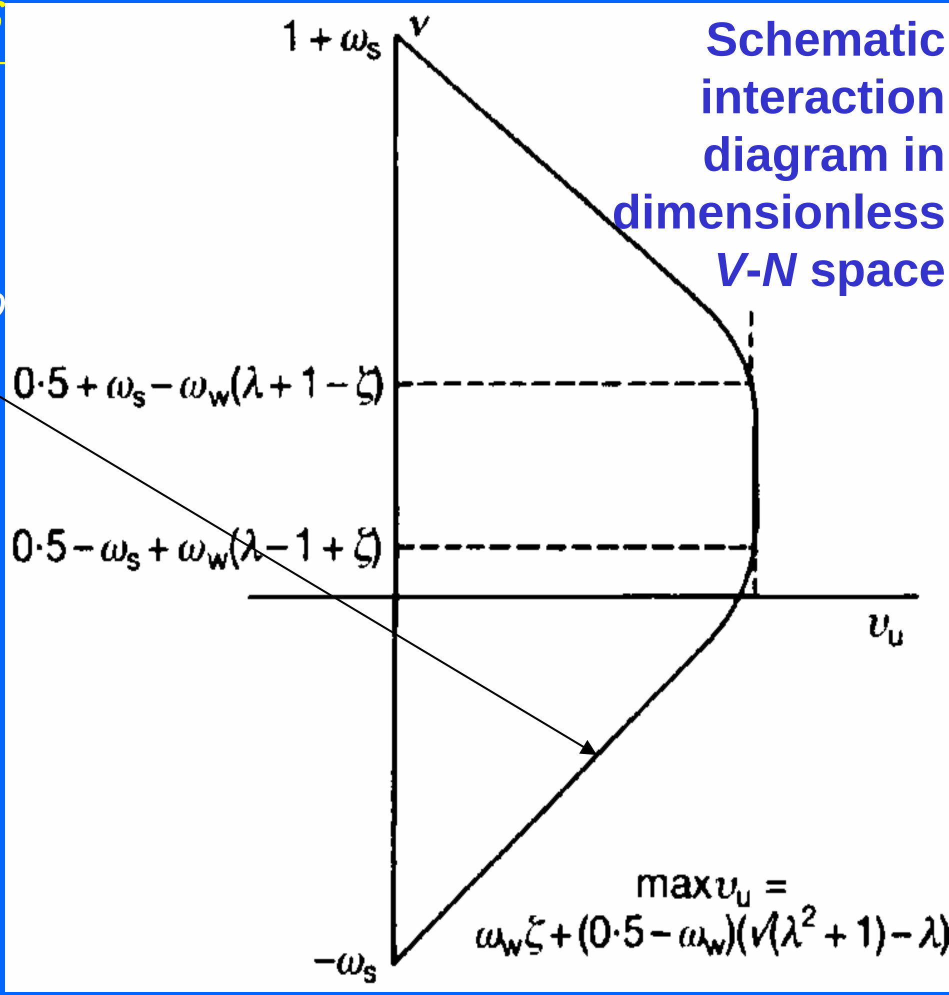
$$\tan\phi = \min\left(\sqrt{\left(\frac{L_s}{\eta h}\right)^2 + \frac{1-\eta}{\eta}} - \frac{L_s}{\eta h},\ \frac{h}{2L_s}\right)$$

where:

$$\eta = \frac{N + A_{s,tot} f_y - \rho_w f_{yw} b_w (2L_s + z\cot\delta)\cot\delta}{b_w h\left(nf_c - \rho_w f_{yw}\left(1+\cot^2\delta\right)\right)}$$

& ultimate shear is:

V_R= $(N+A_{s,tot}f_y)\tan\varphi+\rho_w f_{yw} b_w \cot\delta[z-(2L_s+z\cot\delta)\tan\varphi$



Moderately brittle failure:

Concrete fails by diagonal compression, w/ yielding of transverse reinforcement & of tension reinforcement.

Monotonic lateral force resistance of squat members w/ flexure-shear interaction (cont'd)

3. In axial force range: $Nf_c b_w h + A_{s,tot} f_y \geq \boldsymbol{N} \geq N_2$

Strut inclination is:

$$\tan\phi = \min\left(\sqrt{\left(\frac{L_s}{\eta h}\right)^2 + \frac{1-\eta}{\eta}} - \frac{L_s}{\eta h}, \frac{h}{2L_s}\right)$$

where:

$$\eta = \frac{\left(N - A_{s,tot} f_y\right) + \rho_w f_{yw} b_w \left(2L_s - z\cot\delta\right)\cot\delta}{b_w h\left(nf_c - \rho_w f_{yw}\left(1+\cot^2\delta\right)\right)}$$

& ultimate shear is:

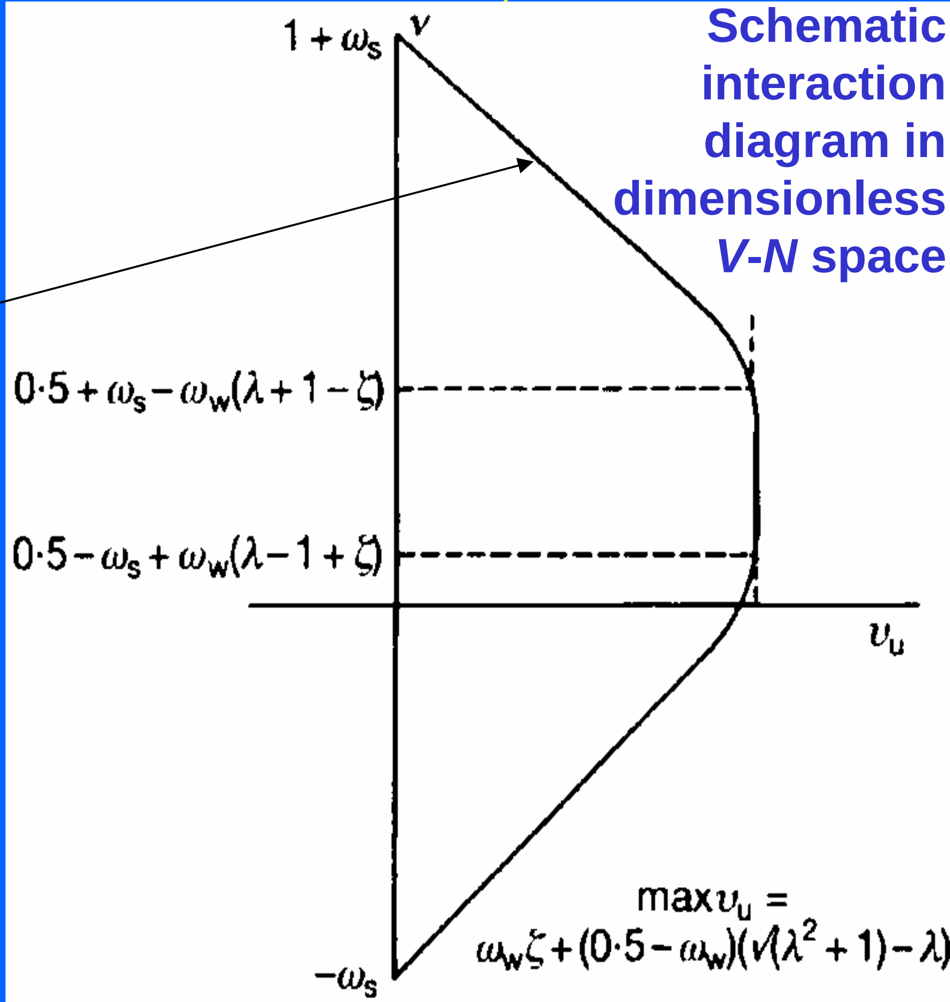
V_R= $(N\text{-}A_{s,tot}f_y)\tan\varphi+\rho_w f_{yw} b_w \cot\delta[z+(2L_s\text{-}z\cot\delta)\tan\varphi]$

<u>Moderately brittle failure:</u>
Concrete fails by diagonal compression, w/ yielding of transverse reinforcement & of compression reinforcement.

If shear effects unimportant ($L_s/h>>2.5$), interaction diagram degenerates into simple μ-v diagram:

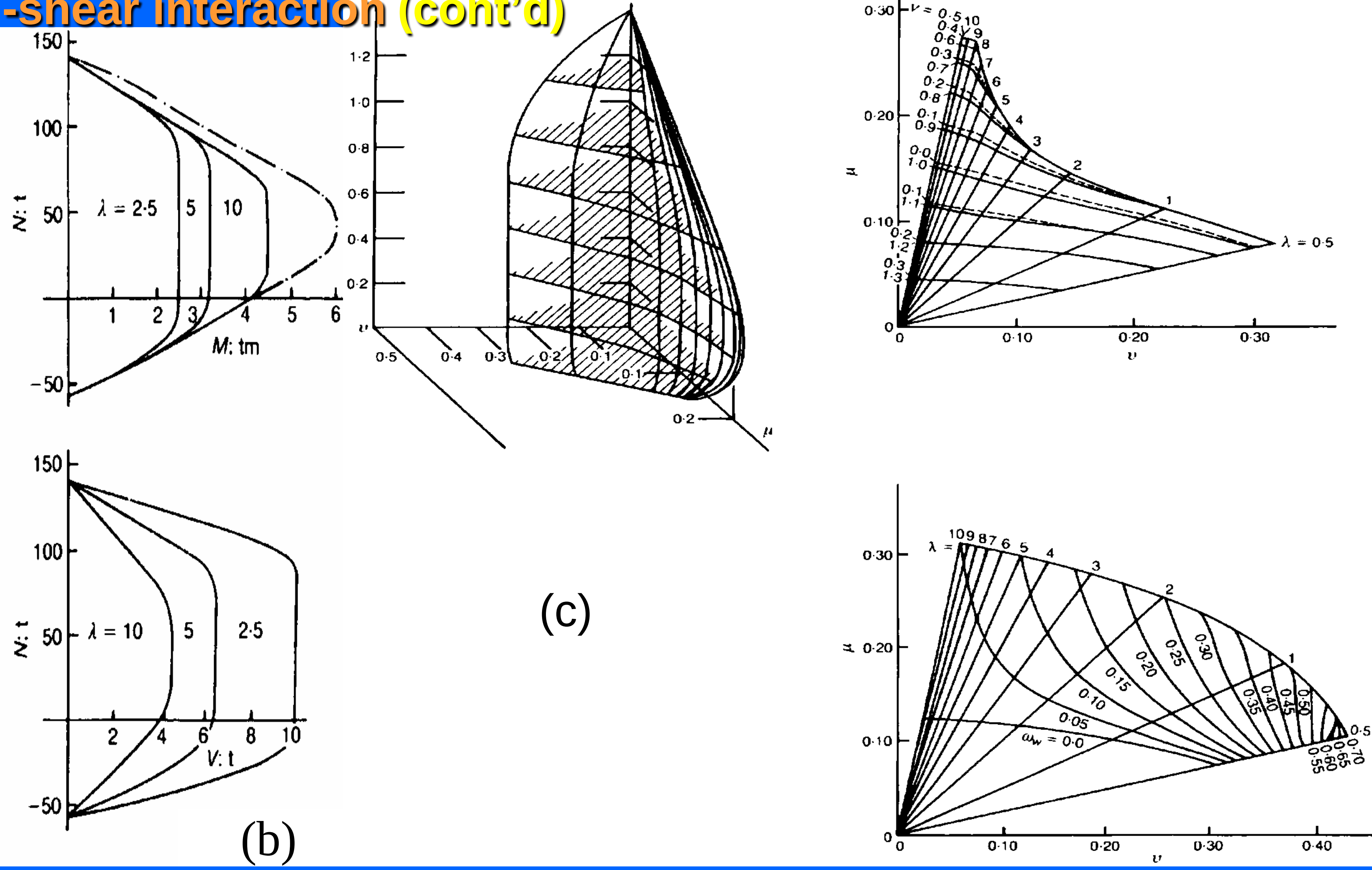
$\mu=0.5\zeta(v+\omega_{tot})$ for $0.5n>v\geq-\omega_{tot}$

$\mu=0.5\zeta(n+\omega_{tot}-v)$ for $n+\omega_{tot}\geq v\geq 0.5n$



Schematic interaction diagram in dimensionless *V-N* space

Monotonic lateral force resistance of squat members w/ flexure-shear interaction (cont'd)

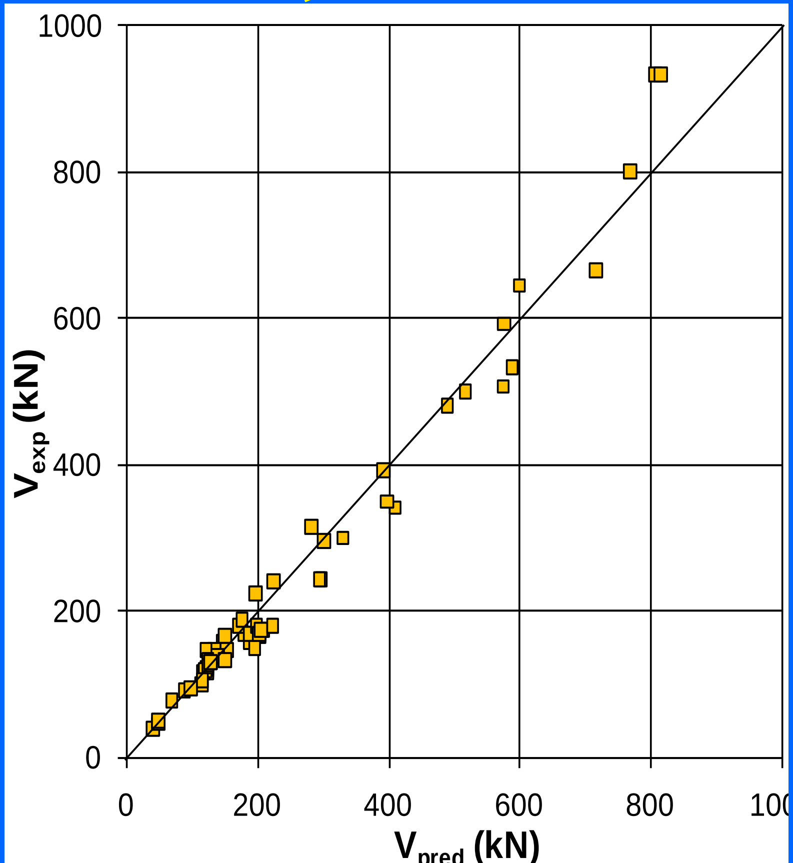


(b) Dimensional interaction *M-N* and *V-N* diagrams of 200mm square column with four 16mm bars; (c) example dimensionless *M-V-N* diagrams

Cyclic shear resistance of squat columns in diagonal compression after flexural yielding

δ = angle of column diagonal to member axis: $\tan\delta = h/2L_s$

$$V_{R,\max} = \frac{4}{7}\left(1-0.02\min\left(5;\mu_\theta^{pl}\right)\right)\left(1+1.35\frac{N}{A_c f_c}\right)\left(1+0.45\cdot 100\rho_{tot}\right)\sqrt{\min\left(f_c;40\right)}\,b_w z \sin 2\delta$$



Experimental cyclic shear resistance for shear compression failure of squat columns after flexural yielding v predictions

no. tests: 64, median=1.00, CoV=10.4%

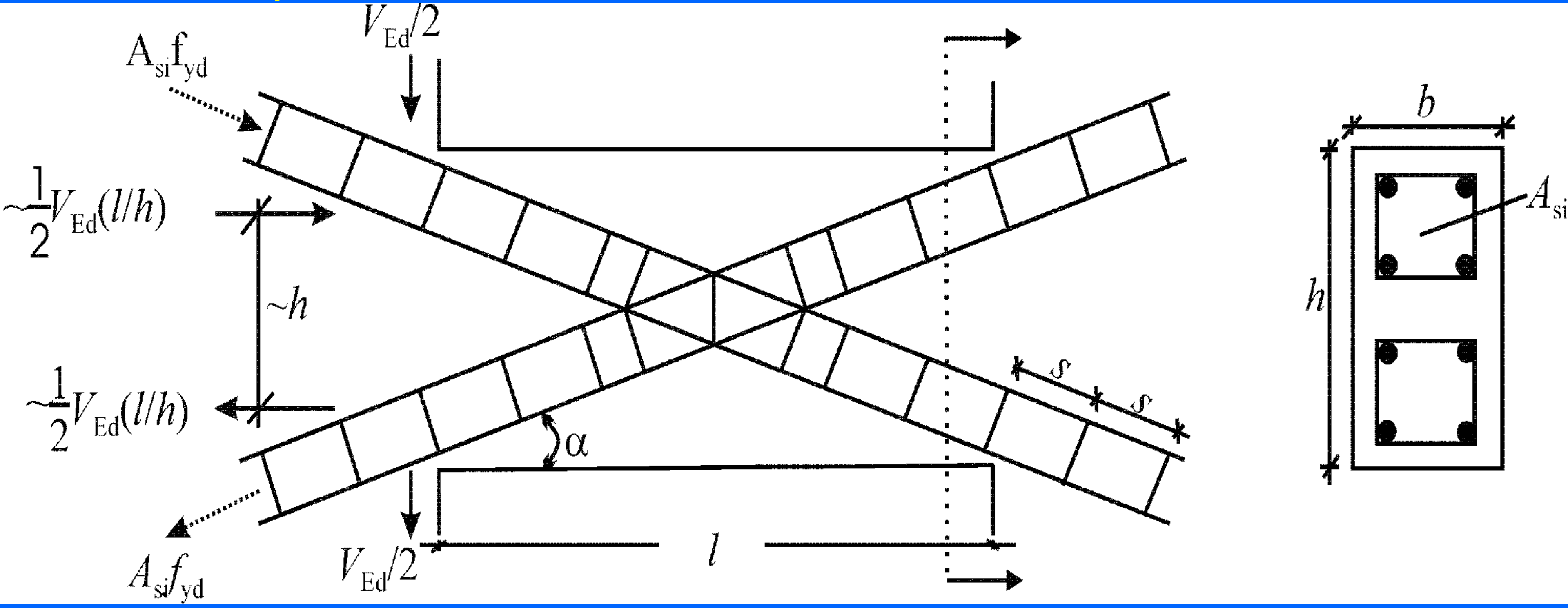
Monotonic lateral force resistance of squat members w/ flexure-shear interaction (cont'd)

Diagonal reinforcement in squat columns or deep beams

$V_{Ed}=2A_{sd}f_{yd}\sin\delta$

$(\tan\delta = z/L = z/2L_s)$

$M_d=zA_{sd}f_{yd}\cos\delta$



Coupling beams w/ diagonal reinforcement in Eurocode 8