INTERNATIONAL SYMPOSIUM

Recent Advances in Structural Design
in Regions of Low-to-Moderate Seismicity

Simplified Shear Wall Detailing in Low-to-moderate Seismicity Regions

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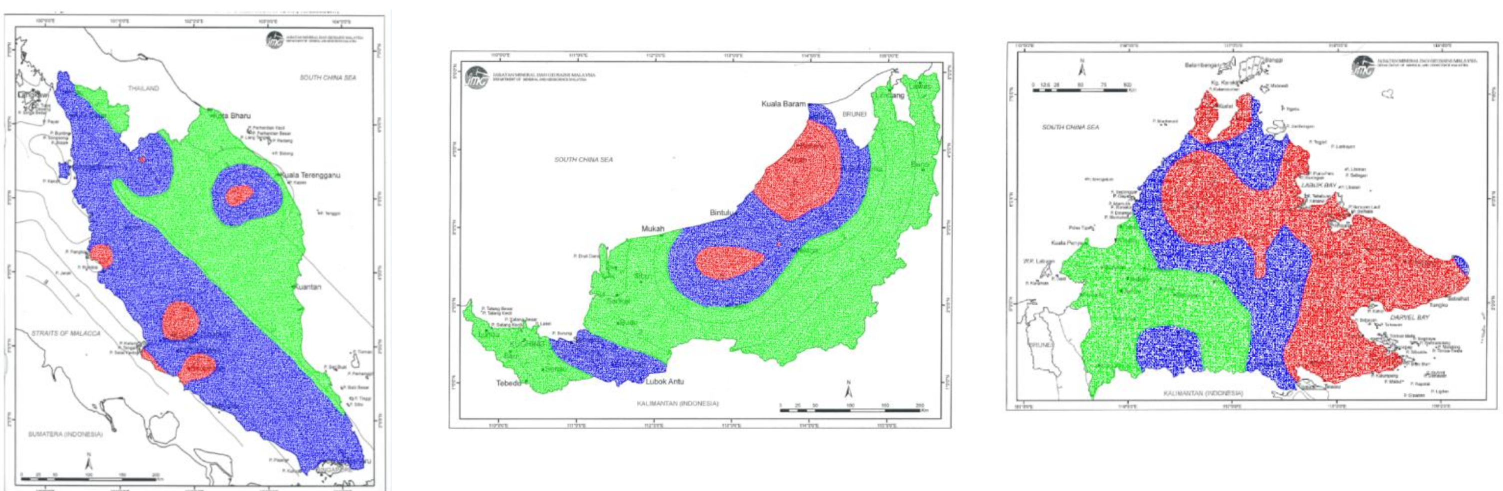
Content

The **prescriptive approach** in conventional seismic codes of practice

Example: Eurocode 8 (EC8) mandating ductility class medium (DCM) detailing by tying with seismic hazard level

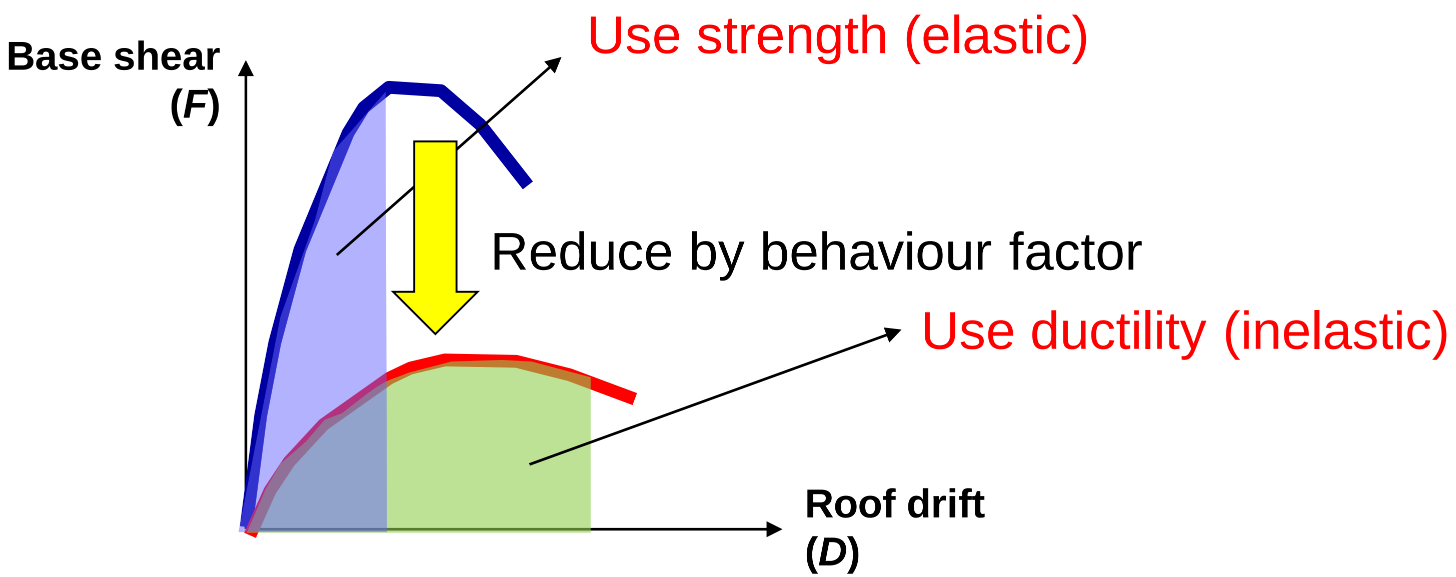
For building importance class III with importance factor, $\gamma_I = 1.2$ & soil factor, $S = 1.35$



VERY LOW SEISMICITY	:	$a_g.S < 0.05$ g	EC2 RC
LOW SEISMICITY	:	$0.05 \text{ g} < a_g.S < 0.10$ g	EC8 DCL
LOW TO MEDIUM SEISMICITY	:	$0.10 \text{ g} < a_g.S$	EC8 DCM

Restricting the use of strength to trade off with ductility

- The code '**should**' allow engineers to have the choice of increasing the design strength rather than mandating ductility design.



Providing an "exit" for engineers

- International seismic codes (e.g. EC8) is restrictive in tying ductile detailing with level of seismicity.
- This work is produced with referenced to EC8 to assist engineers in dealing with ductile detailing.
- Hong Kong has many wall-dominated buildings ($\geq$ 50% base shear taken by walls), hence simplified shear wall ductile detailing is discussed this presentation.

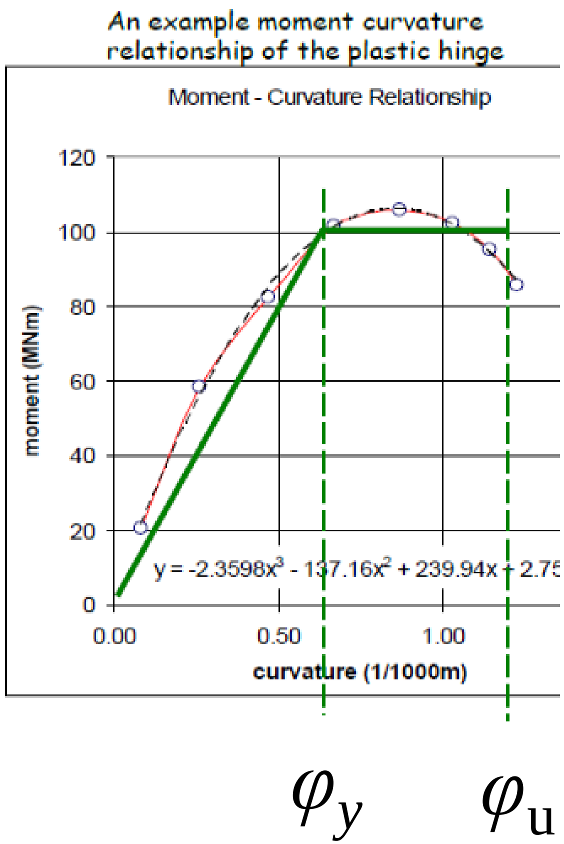
Content

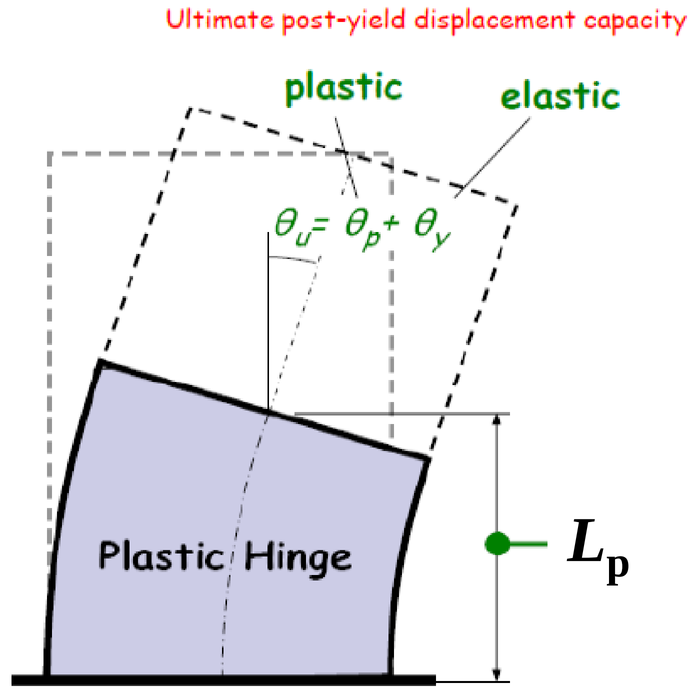
1. Introduction
2. Curvature ductility demand
3. Tools for simplified shear wall local ductility detailing
4. Proposal for deemed-to-comply simplified solution
5. Limitations and assumptions
6. Conclusion

Defining moment-curvature

Elastic bending theory: $M / I = f / y = E / R$, where curvature $\varphi_y = 1 / R$.

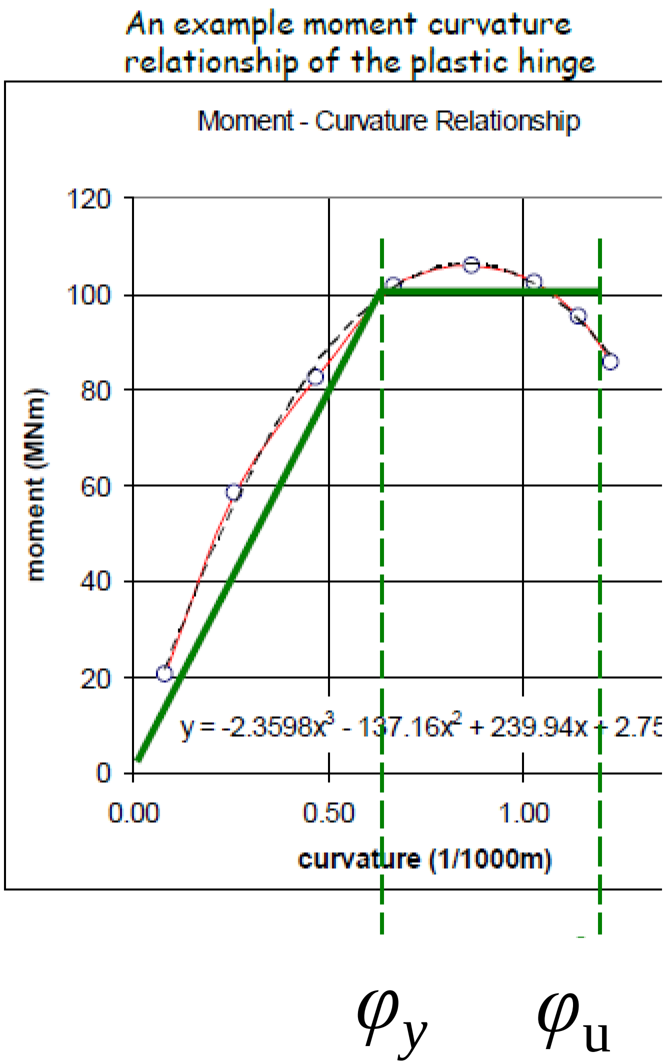
In plastic region, it is normally derived by rotation-to-plastic hinge length ratio ($\varphi_p = \theta_p / L_p$)





$$\theta_p = (\varphi_u - \varphi_y)\, L_p$$

Defining curvature ductility



Curvature ductility

$$\mu_\varphi = \varphi_u / \varphi_y$$

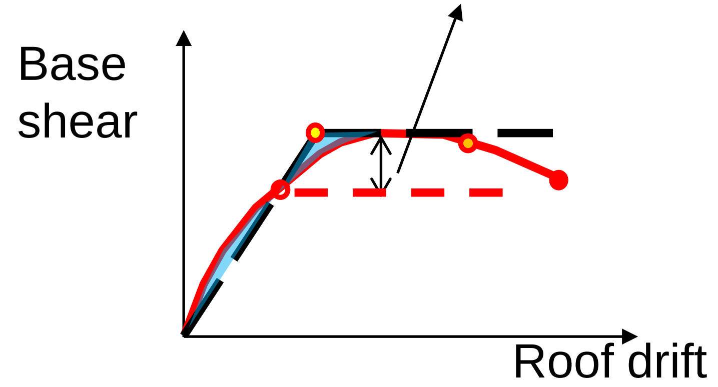
Local curvature ductility demand

- Behaviour factor for walls in EC8:

Table 5.1: Basic value of the behaviour factor, q_o, for systems regular in elevation

STRUCTURAL TYPE	DCM	DCH
Frame system, dual system, coupled wall system	$3,0\alpha_u/\alpha_1$	$4,5\alpha_u/\alpha_1$
Uncoupled wall system	3,0	$4,0\alpha_u/\alpha_1$
Torsionally flexible system	2,0	3,0
Inverted pendulum system	1,5	2,0

$\Omega = \alpha_u / \alpha_1$



Overstrength, $\alpha_u/\alpha_1 = 1.2$

Behaviour factor, $q_o = 3.0\ \alpha_u/\alpha_1 = 3.6$

Account for transfer structure, $q_o = 0.8(3.6) = 2.9$

- Local curvature ductility demand

$\mu_\varphi = 2q_o - 1$ for $T_1 \geq T_C$

$\mu_\varphi = 1 + 2(q_o - 1)\ T_C/T_1$ for $T_1 < T_C$

Class of rebars according to EC2 (or very similar in CS2 of HK)

ANNEX C (Normative)

Properties of reinforcement suitable for use with this Eurocode

C.1 General

(1) Table C.1 gives the properties of reinforcement suitable for use with this Eurocode. The properties are valid for temperatures between -40ºC and 100ºC for the reinforcement in the finished structure. Any bending and welding of reinforcement carried out on site should be further restricted to the temperature range as permitted by EN 13670.

Table C.1: Properties of reinforcement

Product form		Bars and de-coiled rods			Wire Fabrics			Requirement or quantile value (%)
Class		A	B	C	A	B	C	-
Characteristic yield strength f_{yk} or $f_{0,2k}$ (MPa)		400 to 600						5,0
Minimum value of $k = (f_t/f_y)_k$		≥1,05	≥1,08	≥1,15 <1,35	≥1,05	≥1,08	≥1,15 <1,35	10,0
Characteristic strain at maximum force, ε_{uk} (%)		≥2,5	≥5,0	≥7,5	≥2,5	≥5,0	≥7,5	10,0
Bendability		Bend/Rebend test			-			
AC2 Shear strength		-			0,25 $A f_{yk}$ (A is area of wire)			Minimum AC2
Maximum deviation from nominal mass (individual bar or wire) (%)	Nominal bar size (mm) ≤ 8 > 8	± 6,0 ± 4,5						5,0

Note: The values for the fatigue stress range with an upper limit of βf_{yk} and for the Minimum relative rib area for use in a Country may be found in its National Annex. The recommended values are given in Table C.2N. The value of β for use in a Country may be found in its National Annex. The recommended value is 0,6.

Class B rebar

(common in Malaysia and Hong Kong)

***Note that f_{yk} is between 400 to 600 MPa**

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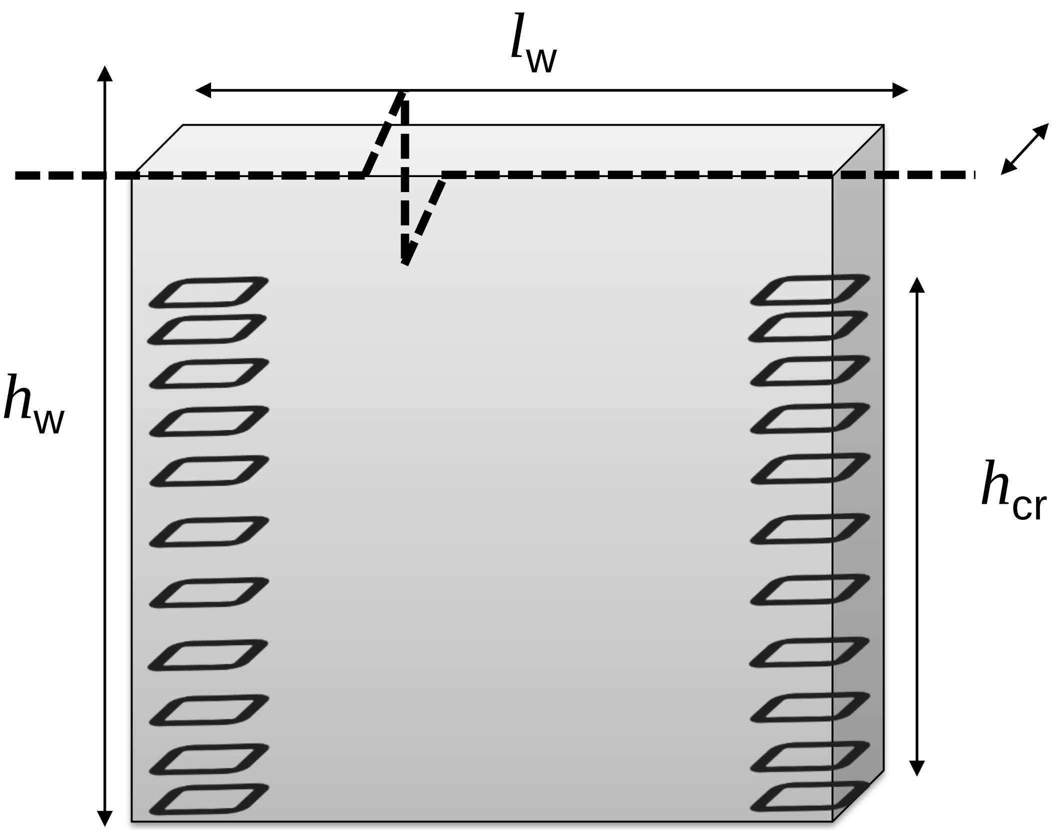
Parametric boundaries

- Wall thickness (b_c): 200 mm to 1000 mm
- Cover: 20 mm to 60 mm
- Longitudinal rebar diameter (d_{bL}): 10, 12, 16, 20, 25 mm
- Hoop rebar diameter (d_{hoop}): 10, 12, 16 mm
- Steel characteristic yield strength (f_{yk}): 500 MPa
- Concrete grade ($f_{cu,k}$): 25 to 90 Mpa
- Steel safety factor (γ_s): 1.15
- Concrete safety factor (γ_c): 1.5
- Steel design yield strain (ε_{yk}): 0.002
- Normalised axial load (ν_d): 0.1 to 0.4

Critical plastic hinge height (h_{cr})

$h_{cr} = \max\{l_w; h_w / 6)$ $\leq 2\, l_w$

$\leq 2\, h_s$ *$^*h_s$ is clear storey height*



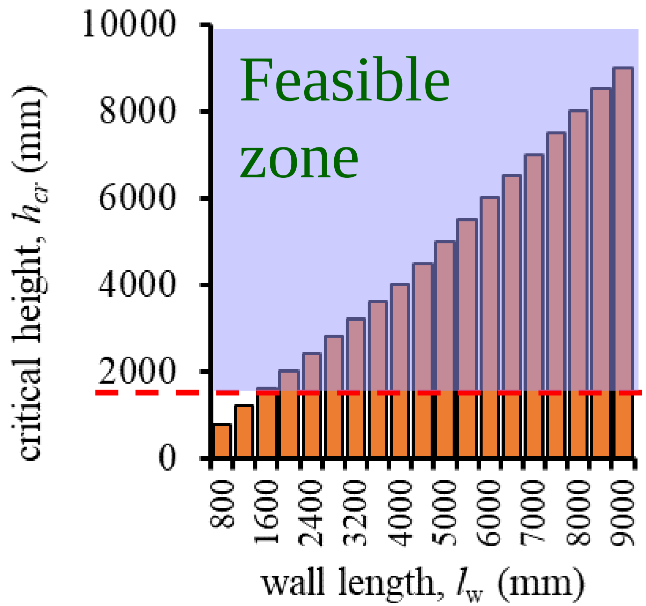
Wall: $l_w / b_c \geq 4$

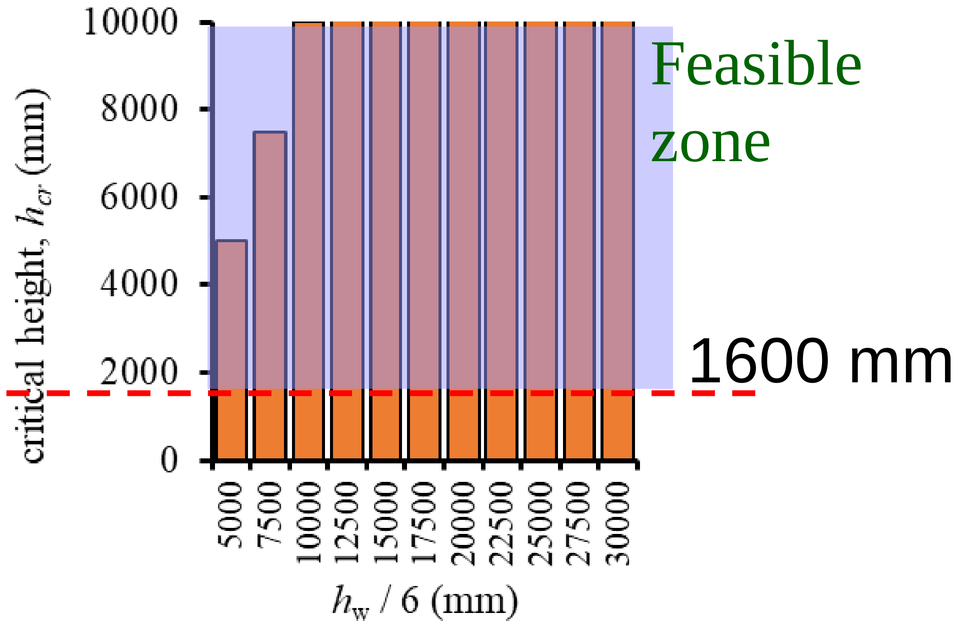
Similar to the definition in HK CoP 2013

Critical plastic hinge height (h_{cr})

Example:

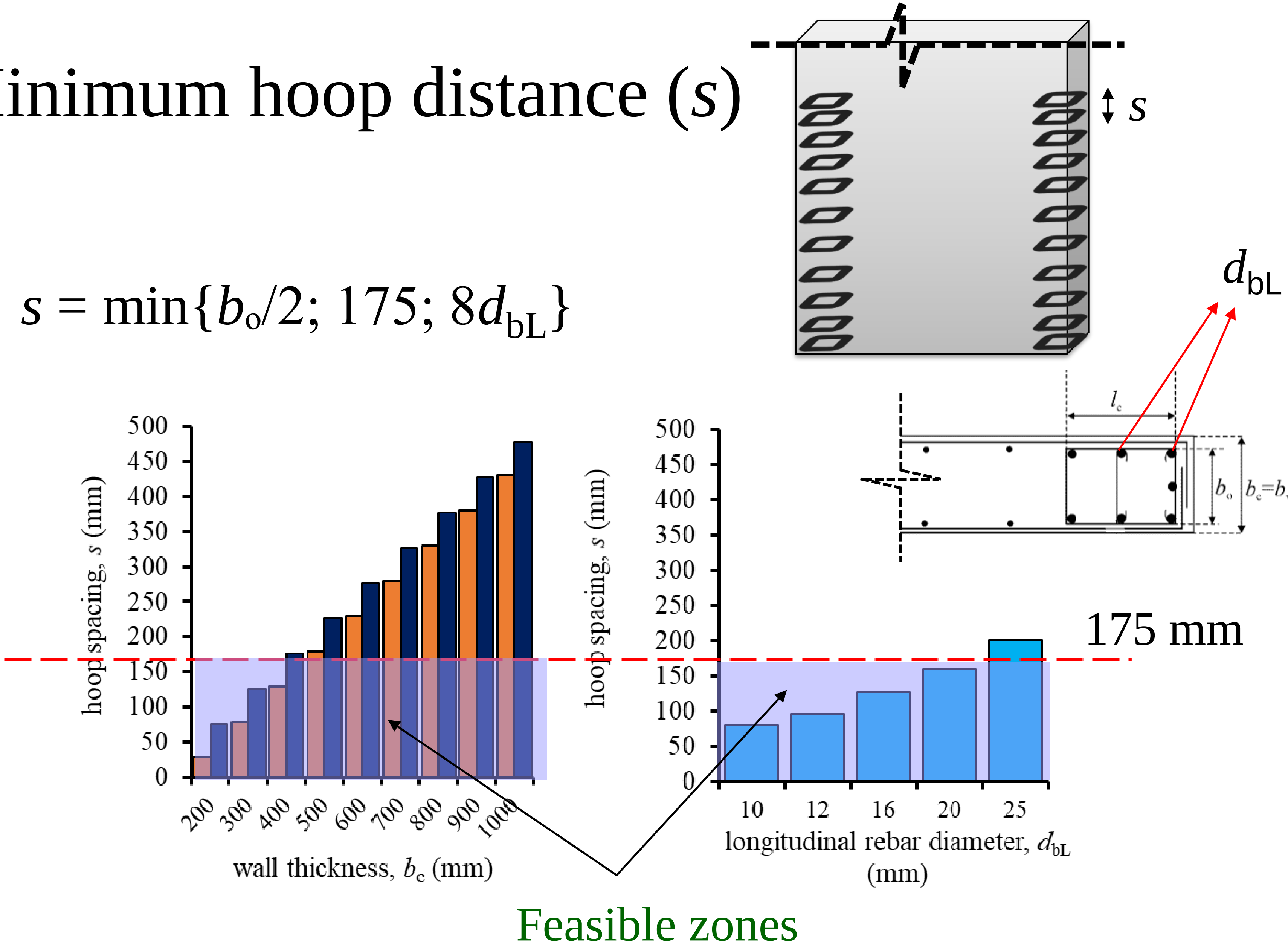
- Taking minimum wall thickness 200 mm
- Minimum wall length is 800 mm
- At least 10 storeys for wall buildings, $h_w \geq 30$ m





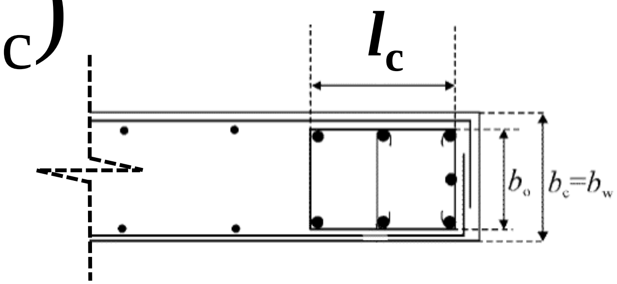
Minimum hoop distance (s)

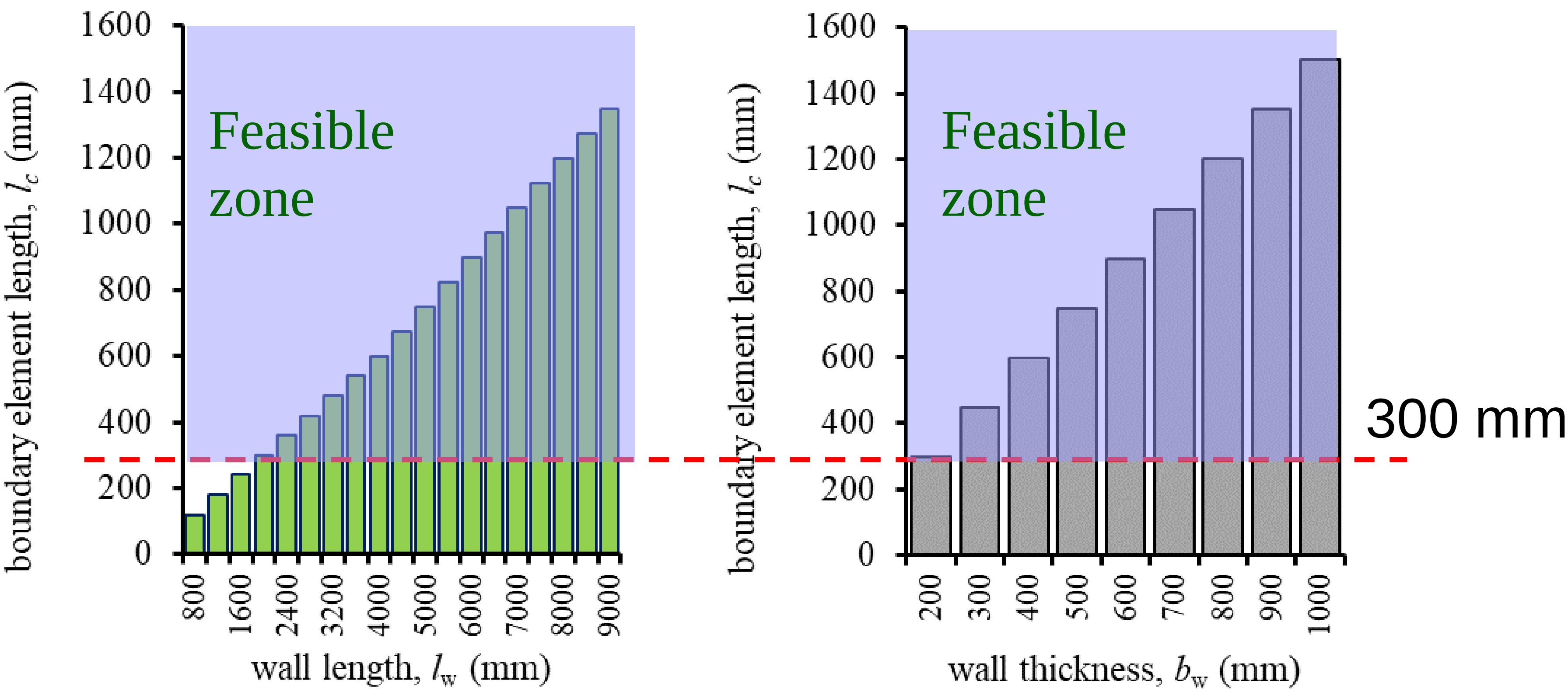
$$s = \min\{b_o/2;\ 175;\ 8d_{bL}\}$$



Boundary element length (l_c)

$$l_c = \max\{0.15 l_w; 1.5 b_w\}$$





Confinement to achieve the curvature ductility in shear walls according to EC8

Confinement capacity, C_c $\geq$ Confinement demand, C_d

$$\alpha\, \omega_{wd} \geq [30\, \mu_\varphi\, (v_d + \omega_v)\, \varepsilon_{sy,d}\, b_c/b_o] - 0.035$$

$$(\alpha_n\, \alpha_s)\, \omega_{wd} \geq [30\, \mu_\varphi\, (v_d + \omega_v)\, \varepsilon_{sy,d}\, b_c/b_o] - 0.035$$

Where

α_n	= confinement effective factor for longitudinal engaged bar spacing
α_s	= confinement effective factor for stirrups spacing
ω_{wd}	= mechanical volumetric ratio of confining hoops within the critical regions
μ_φ	= curvature ductility
v_d	= normalised design axial force
ω_v	= mechanical ratio of vertical rebars in the web
$\varepsilon_{sy,d}$	= design value of tension steel strain at yield
b_c/b_o	= width of gross sectional area to width of confined core

Steps explained in simple terms:

STEP 1:

Ductility demand (μ_φ)

Required input:

q_o, T_1, RSA graph

STEP 2:

Confinement demand (C_d)

Required input:

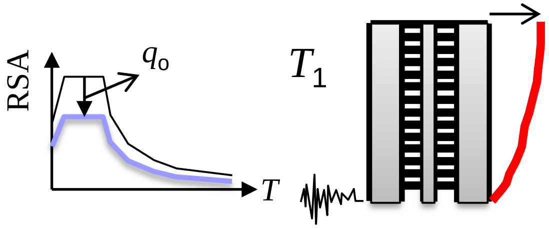
μ_φ, ν_d, ω_v

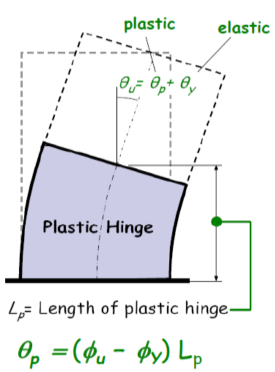
STEP 3:

Confinement capacity (C_c)

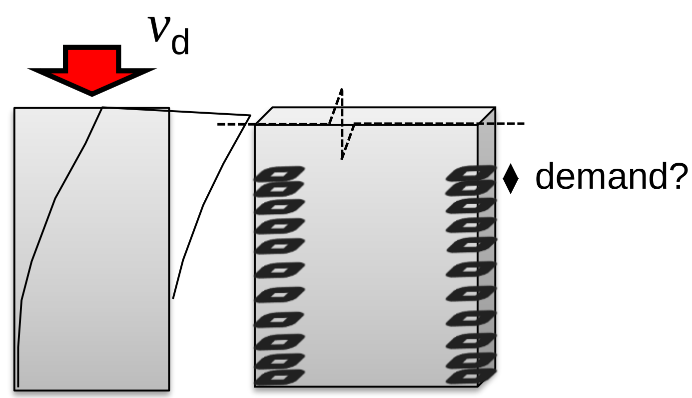
Required input:

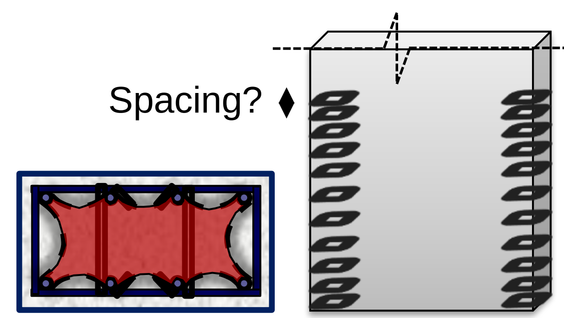
α_n, α_s, ω_{wd}





μ_φ





$$C_d = [30\,\mu_\varphi\,(\nu_d + \omega_v)\,\varepsilon_{sy,d}\,b_c/b_o] - 0.035$$

$$C_c = \alpha_n\,\alpha_s\,\omega_{wd}$$

STEP 1:

Ductility demand (μ_φ)

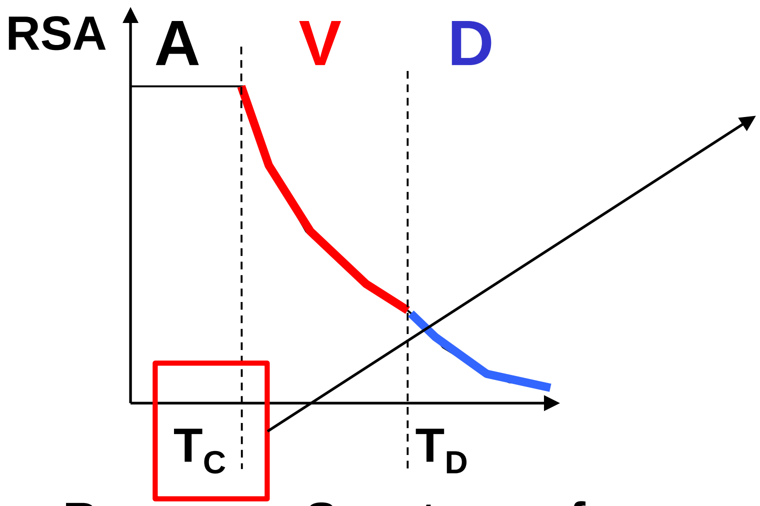
Required input:

q_o, T_1, RSA graph

$$\mu_\varphi = 2q_o - 1 \text{ for } T_1 \geq T_C$$

$$\mu_\varphi = 1 + 2(q_o - 1)\, T_C/T_1 \text{ for } T_1 < T_C$$

**Note: Multiply by 1.5 for Class B rebars*

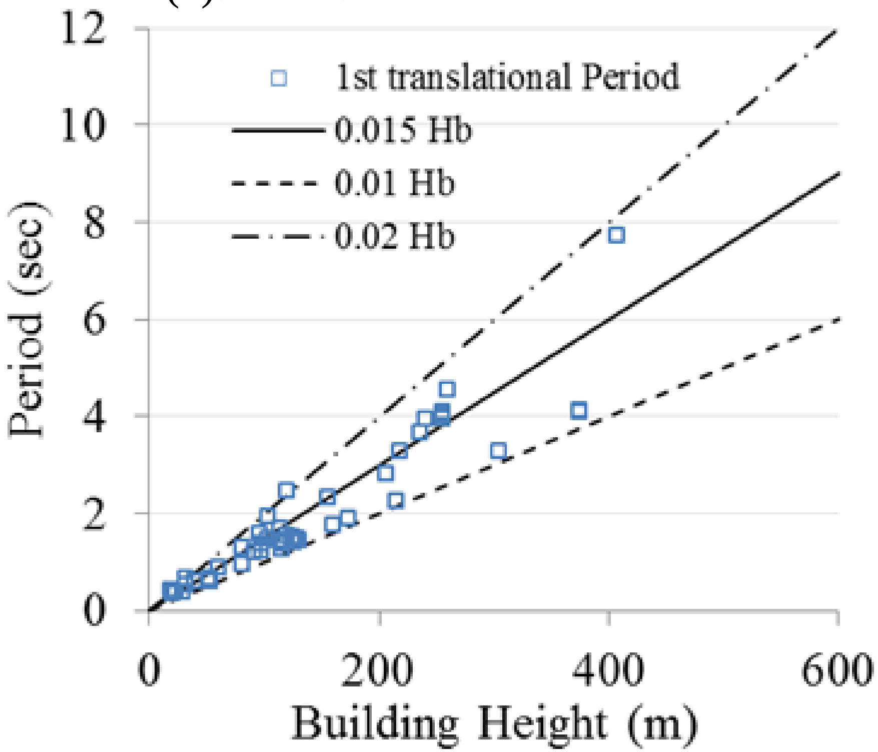


Response Spectrum of Acceleration (RSA)

T_C is typically about 0.25 s to 0.80 s for all ground types

Estimating the structural period of wall buildings (in HK)

Su RKL, Chandler AM, Li JH and Lee PKK (2003). "**Dynamic testing and modelling of existing buildings in Hong Kong**", *HKIE Transactions*, 10(2): 17-25.



$\mathbf{T_1 = 0.01\ H_B \text{ to } 0.02\ H_B}$

Say 20 storeys, 3 m storey height, hence H_B = 60 m

$\mathbf{T_1 = 0.6 \text{ s to } 1.2 \text{ s}}$

(typically 0.9 s)

$\mathbf{> T_C = 0.25 \text{ s to } 0.80 \text{ s}}$

$\mu_\varphi = 2q_o - 1$ **for** $T_1 \geq T_C$

$\mu_\varphi = 1 + 2(q_o - 1)\ T_C/T_1$ **for** $T_1 < T_C$

**Note: Multiply by 1.5 for Class B rebars*

Local curvature ductility demand (Class B rebar)

$\mu_\varphi = 2q_o - 1$ for $T_1 \geq T_C$

Behaviour factor for walls:

$\alpha_u/\alpha_1 = 1.2$; $q_o = 3.0\ \alpha_u/\alpha_1 = 3.6$;

Account for transfer structure, reduce by 20%

Hence, $q_o = 3.6\ (0.8) = 2.9$

$\boldsymbol{\mu_\varphi = (2q_o - 1)\ 1.5}$

**Note: Multiply by 1.5 for Class B rebars*

$\boldsymbol{\mu_\varphi = [2(2.9) - 1]1.5}$

$\boldsymbol{= 7.1}$

STEP 2:

Confinement demand (C_d)

Required input:

μ_φ, v_d, ω_v

C_d is dependent on the normalized design axial force (v_d) and mechanical ratio of vertical rebar (ω_v)

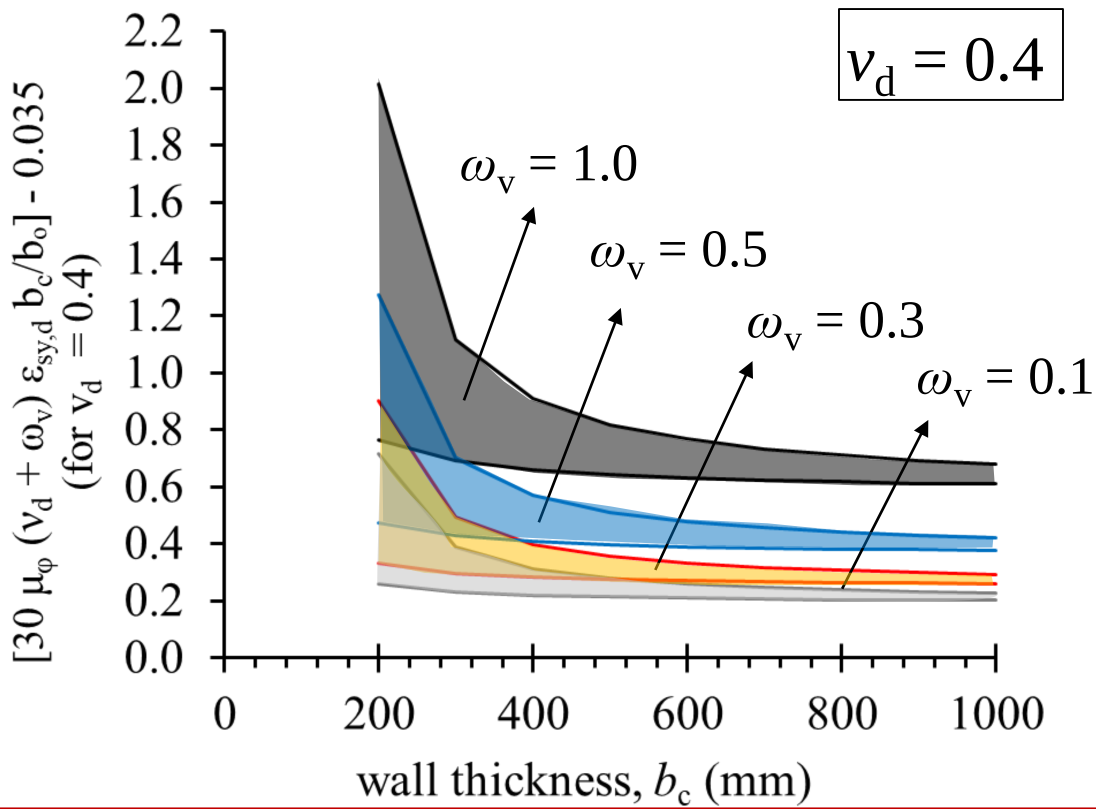


Figure above shows the confinement demand for an example of shear walls with normalized design axial force of $v_d = 0.4$

Confinement demand, C_d

$[30\, \mu_\varphi\, (v_d + \omega_v)\, \varepsilon_{sy,d}\, b_c/b_o] - 0.035$

$\omega_v = \rho_v\, f_{yd,v} / f_{cd}$

Example:

2% vertical rebar

60 MPa cube strength
(50 MPa cylinder strength)

500 MPa steel

$\omega_v = 0.02\,(500/1.15)/(50/1.5)$

$= 0.3$

STEP 3:

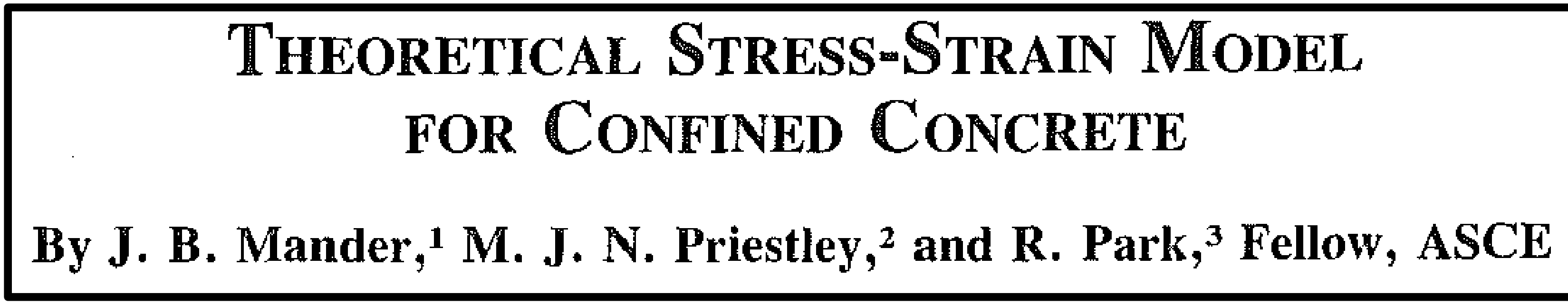
Confinement capacity (C_c)

Required input:

α_n, α_s, ω_{wd}

The input parameters (α_n, α_s, ω_{wd}) to arrive at C_c is slightly more complicated, it will be explained in next few slides.

The effective confinement area for confinement capacity estimation


THEORETICAL STRESS-STRAIN MODEL
FOR CONFINED CONCRETE

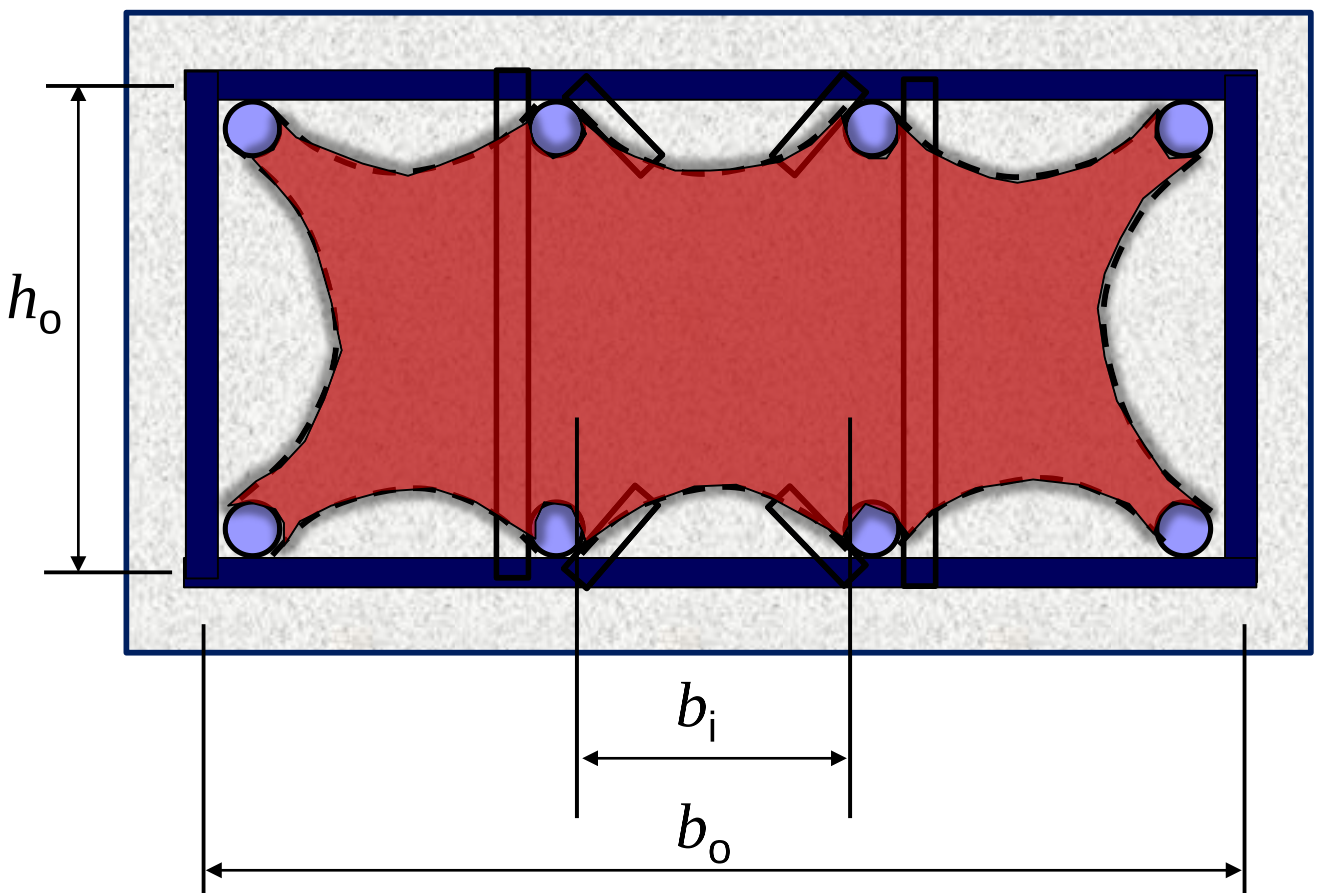
By J. B. Mander,[1] M. J. N. Priestley,[2] and R. Park,[3] Fellow, ASCE

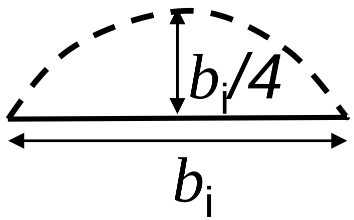
Journal of Structural Engineering

Vol. 114, No. 8, August, 1988

Effective confined area of cross-section at the hoop level of column

Cross-section of column





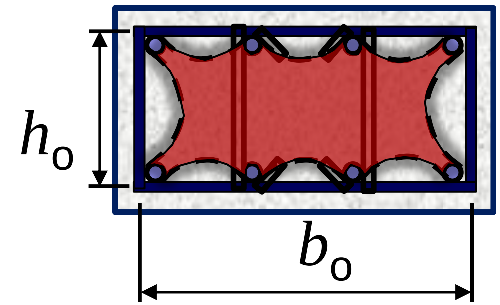
An assumed parabola by Mander et al. (1988)

$A_{parabola} = 2/3\ b_i\ (b_i/4)$

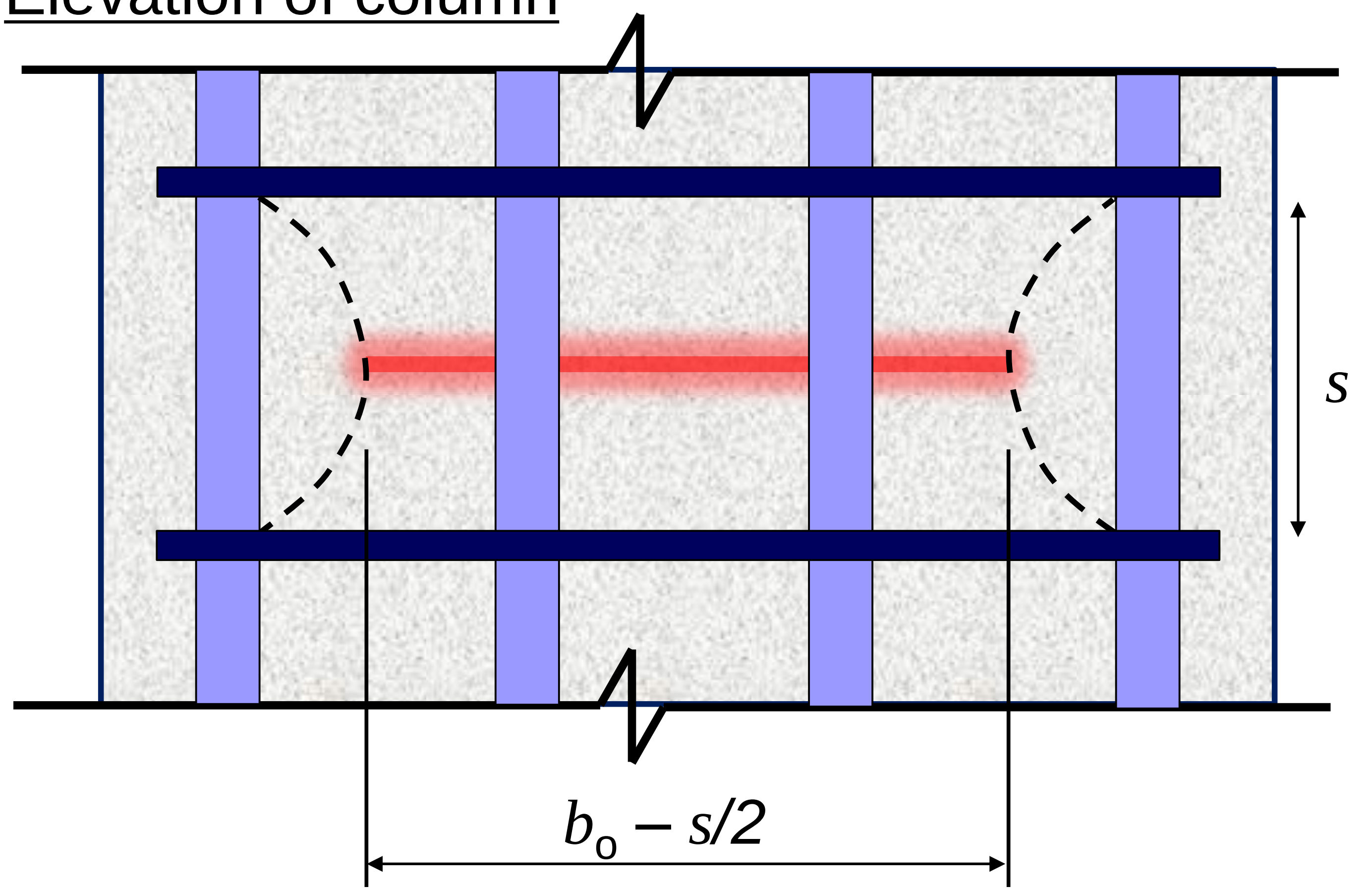
$= b_i^2 / 6$

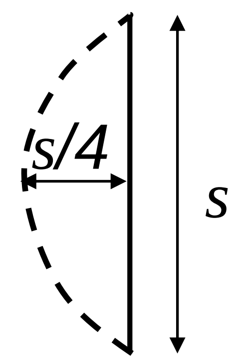
$A_{eff,n} = b_o\ h_o - \sum_i^n (b_i^2 / 6)$

Area reduction along the longitudinal axis of column (b_o direction)



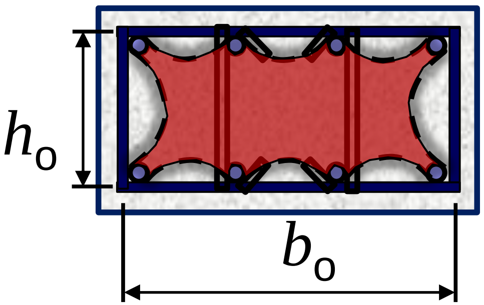
Elevation of column



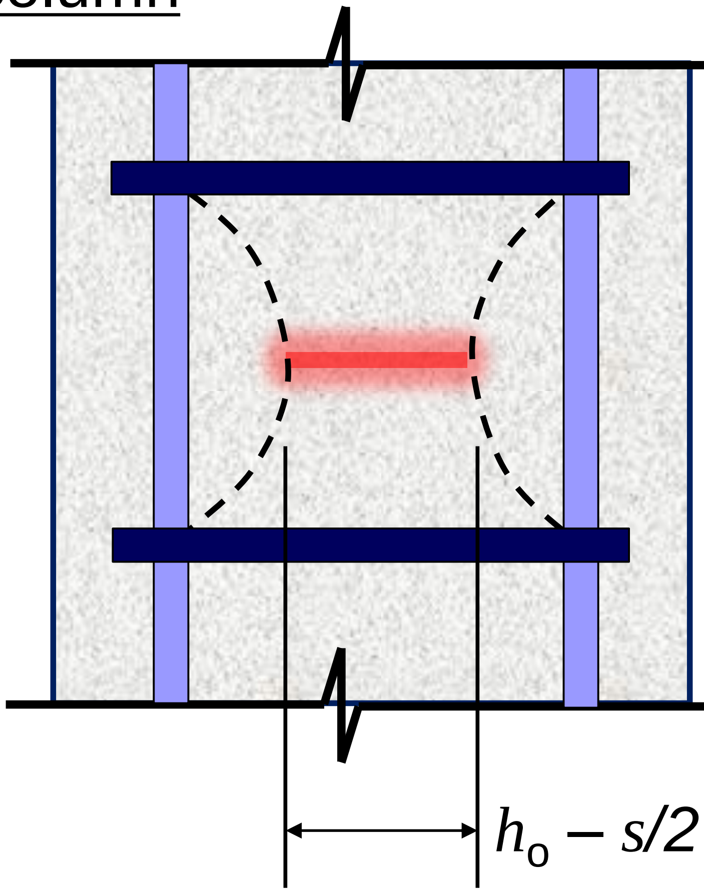


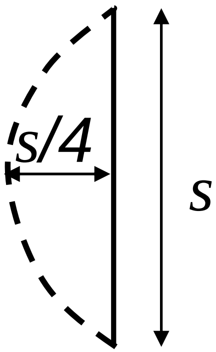
An assumed parabola by Mander et al. (1988)

Area reduction along the longitudinal axis of column (h_o direction)



Elevation of column





An assumed parabola by Mander et al. (1988)

Combined area reduction factors

$A_{eff} = A_{eff,n}$ x (reduction along longitudinal axis)

$= [b_o\, h_o - \sum_i^n (b_i^2 / 6)]\ [(b_o - s/2)/b_o\, (h_o - s/2)/h_o]$

Normalised by $b_o\, h_o$

$\alpha = \underline{[1 - \sum_i^n (b_i^2 / 6)]}\ \underline{[(1 - s/2b_o)\,(1 - s/2h_o)]}$

$= \alpha_n\, \alpha_s$

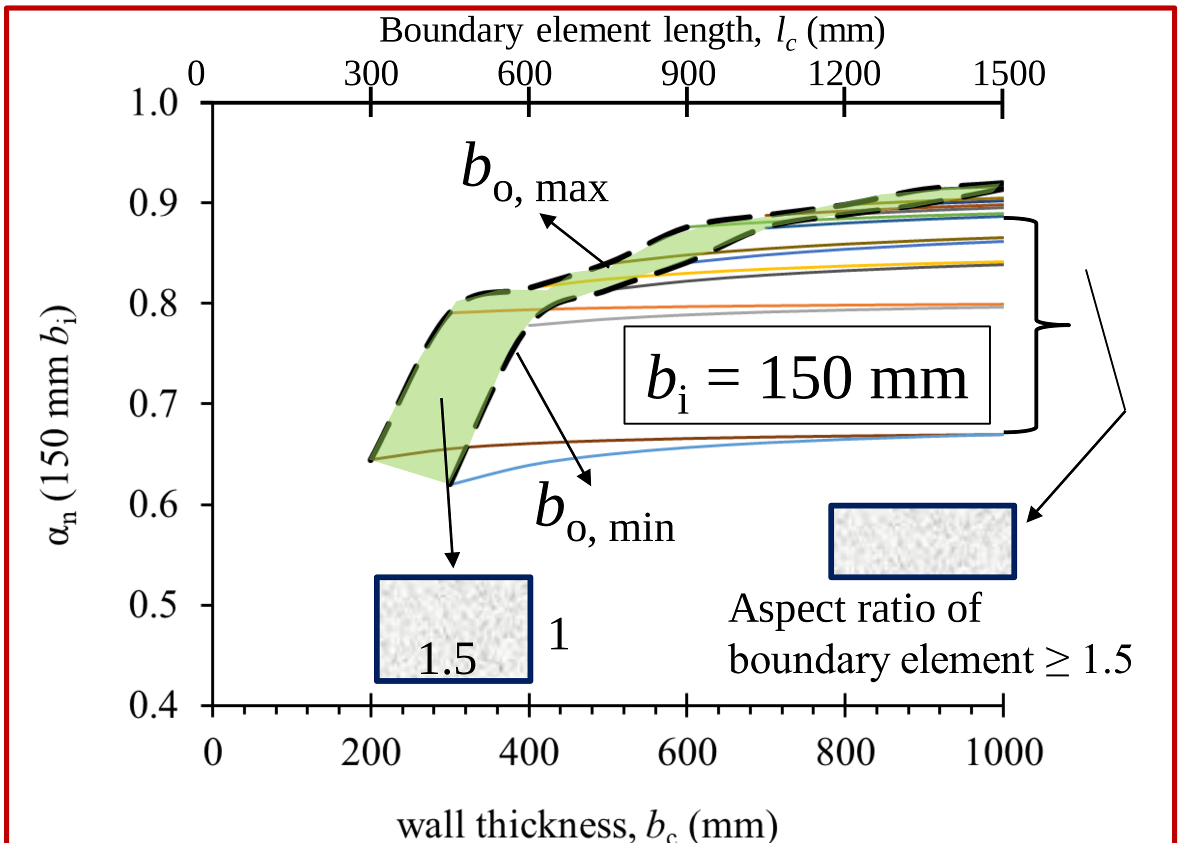
STEP 3a:

Confinement capacity (C_c)

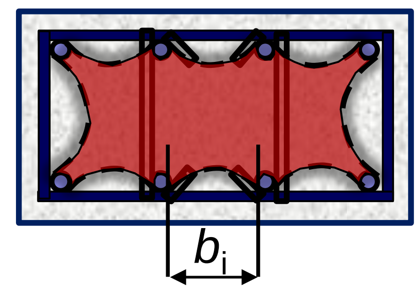
Required input:

$\boldsymbol{\alpha_n}$, α_s, ω_{wd}

α_n is controlled by the horizontal distance (b_i) between consecutive engaged vertical bars



$$\alpha_n = [1 - \sum_i^n (b_i^2 / 6)]$$



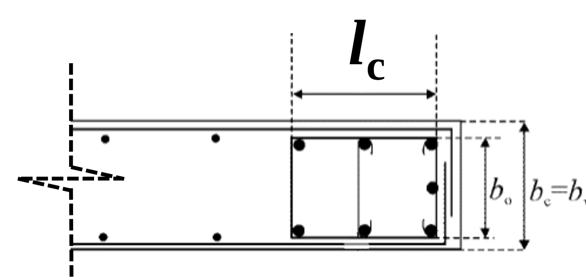


Figure above shows the confined core area reduction factor α_n

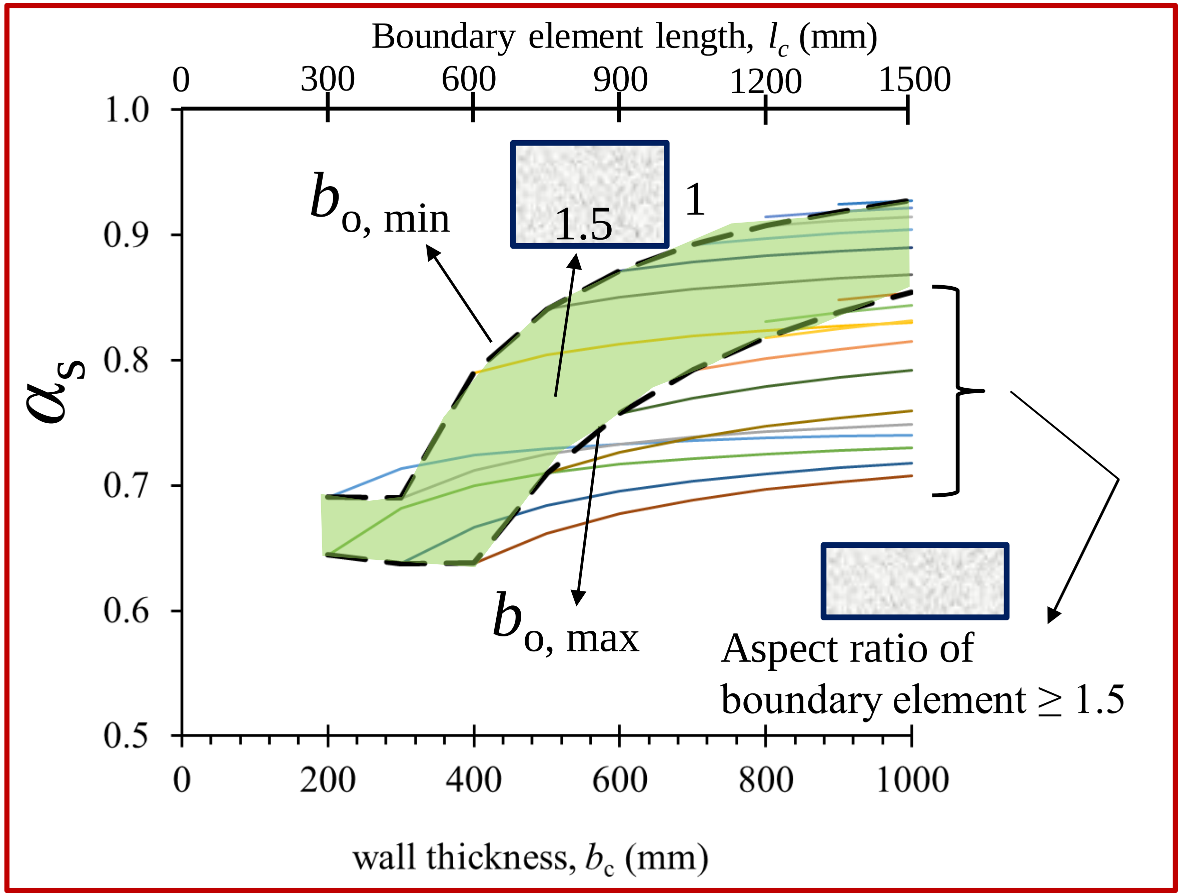
STEP 3b:

Confinement capacity (C_c)

Required input:

α_n, **α_s**, ω_{wd}

α_s is controlled by the vertical spacing (s) of hoops, however s is controlled min{$b_o/2$; 175; $8d_{bL}$}, which resulted in a generic outcome within the boundary element of shear walls.



$$\alpha_s = (1 - s/2b_o)\,(1 - s/2l_c)$$

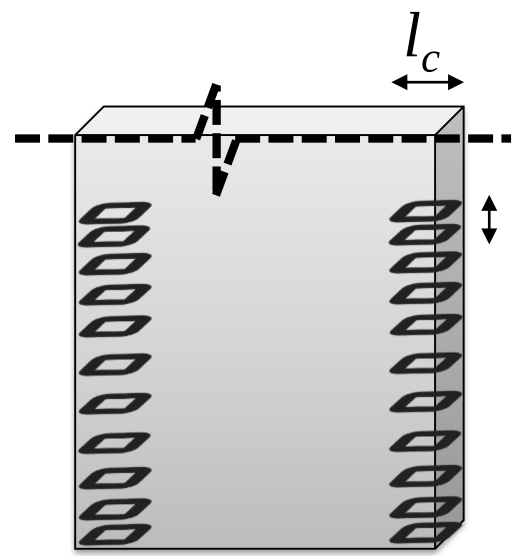


Figure above shows the confined core area reduction factor α_s

STEP 3c:

Confinement capacity (C_c)

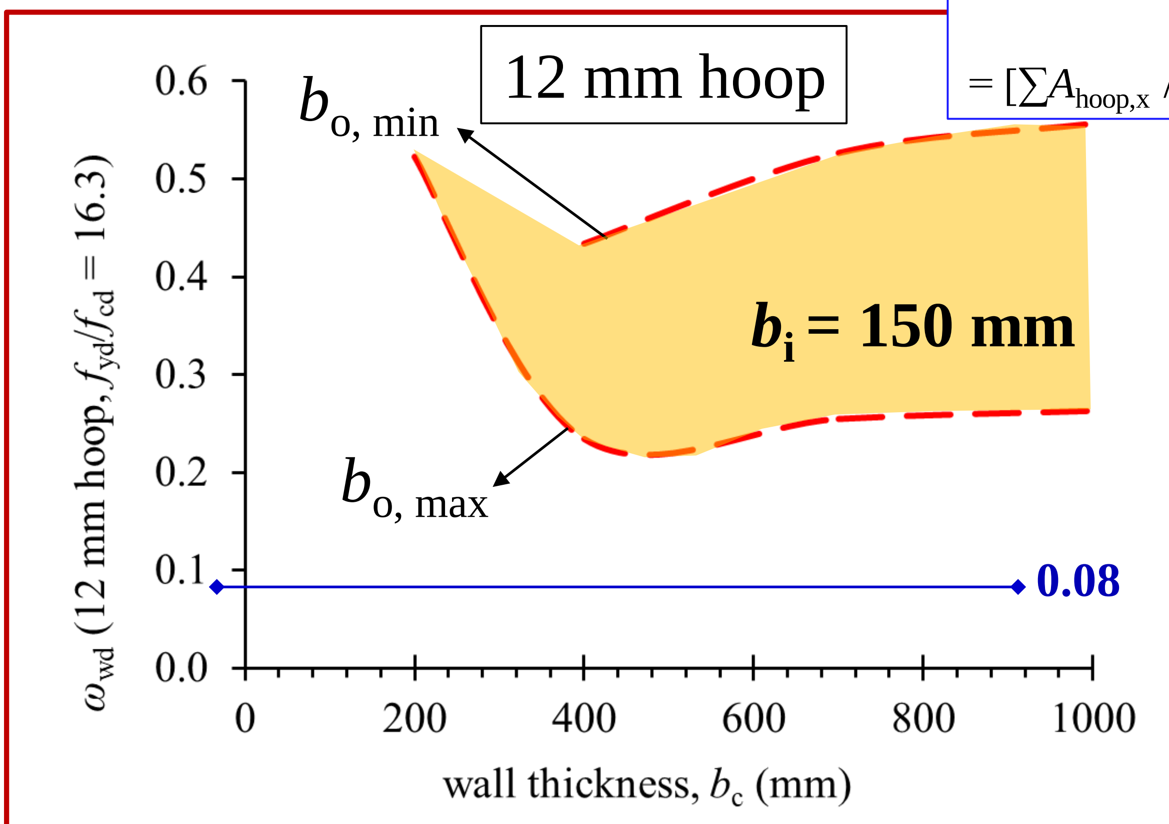
Required input:

α_n, α_s, $\boldsymbol{\omega_{wd}}$

ω_{wd} is controlled by vertical hoop diameter and distance relative to the confined core, with consideration of steel and concrete design strength.

$$\omega_{wd} = (V_{hoop} / V_{core})\,(f_{yd}/f_{cd}) \geq 0.08$$

$$= [\sum A_{hoop,x} / (b_o s)]\,[\sum A_{hoop,y} / (h_o s)]\,(f_{yd}/f_{cd}) \geq 0.08$$



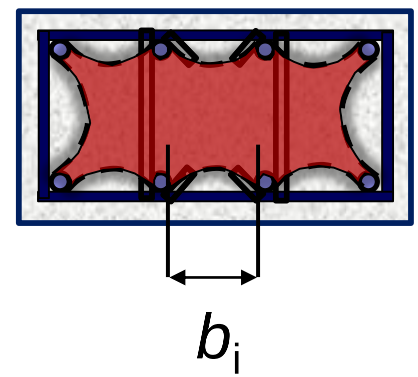


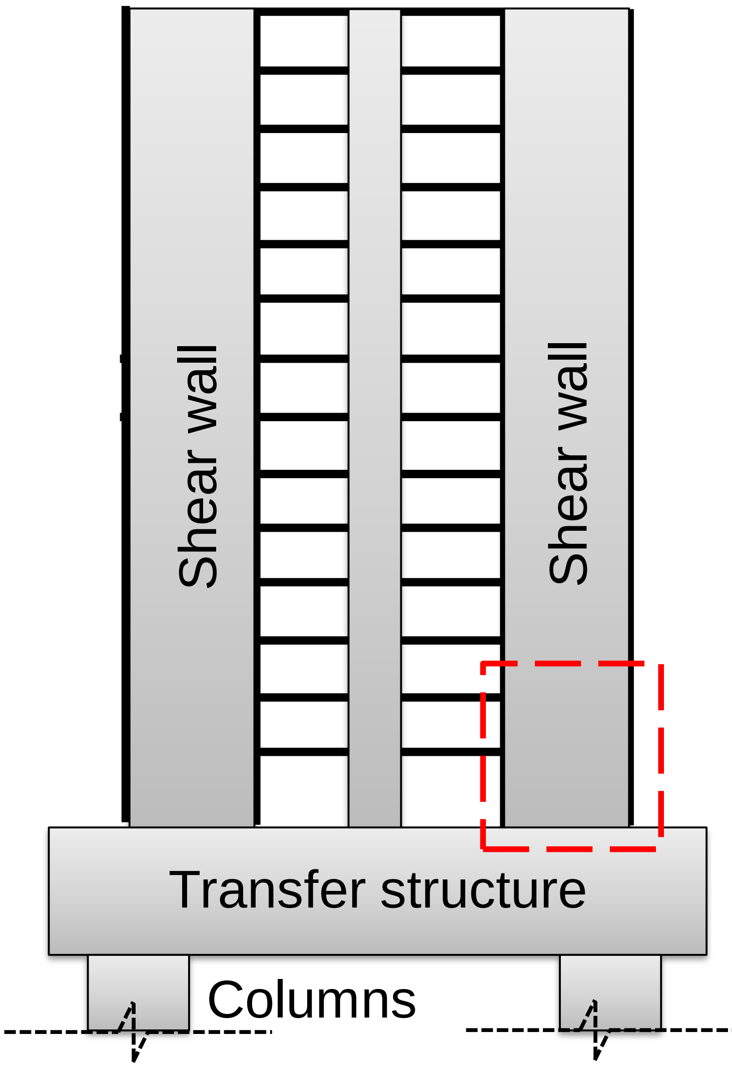
Figure above shows the confinement capacity C_c for $\boldsymbol{f_{yd}/f_{cd}}$ **= 16.3** (for f_{yk} = 500 MPa, f_{ckcube} = 50 Mpa)

Content

Simplified ductile detailing for RC shear walls

Demand

Step 1: Curvature ductility demand (μ_φ)



v_d = 0.4

$f_{y,k}$ = 500 MPa

$f_{cu,k}$ = 50 MPa

Thickness = 400 mm

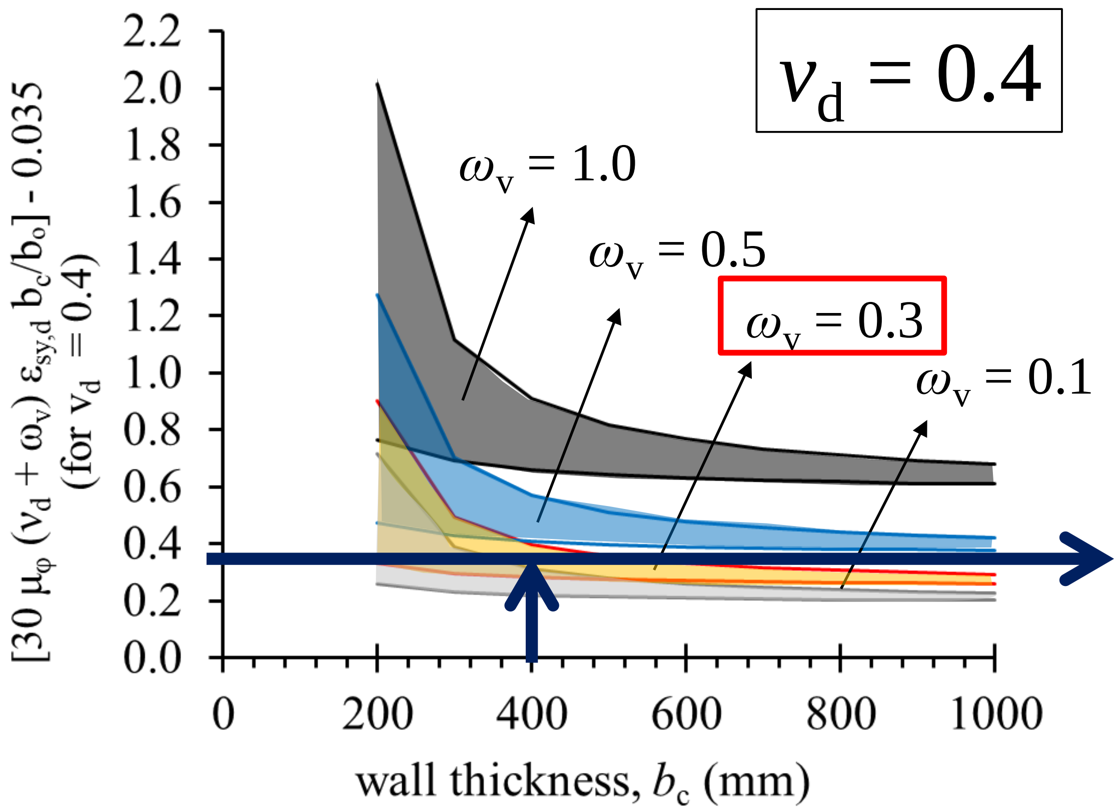
ρ_v = 2%

μ_φ = 7.1 (with transfer structure)

Simplified ductile detailing for RC shear walls

Demand

Step 2: Confinement demand (C_d)



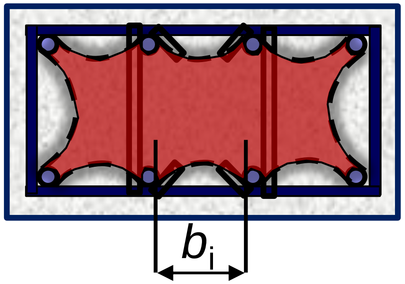
Average confinement demand = 0.35

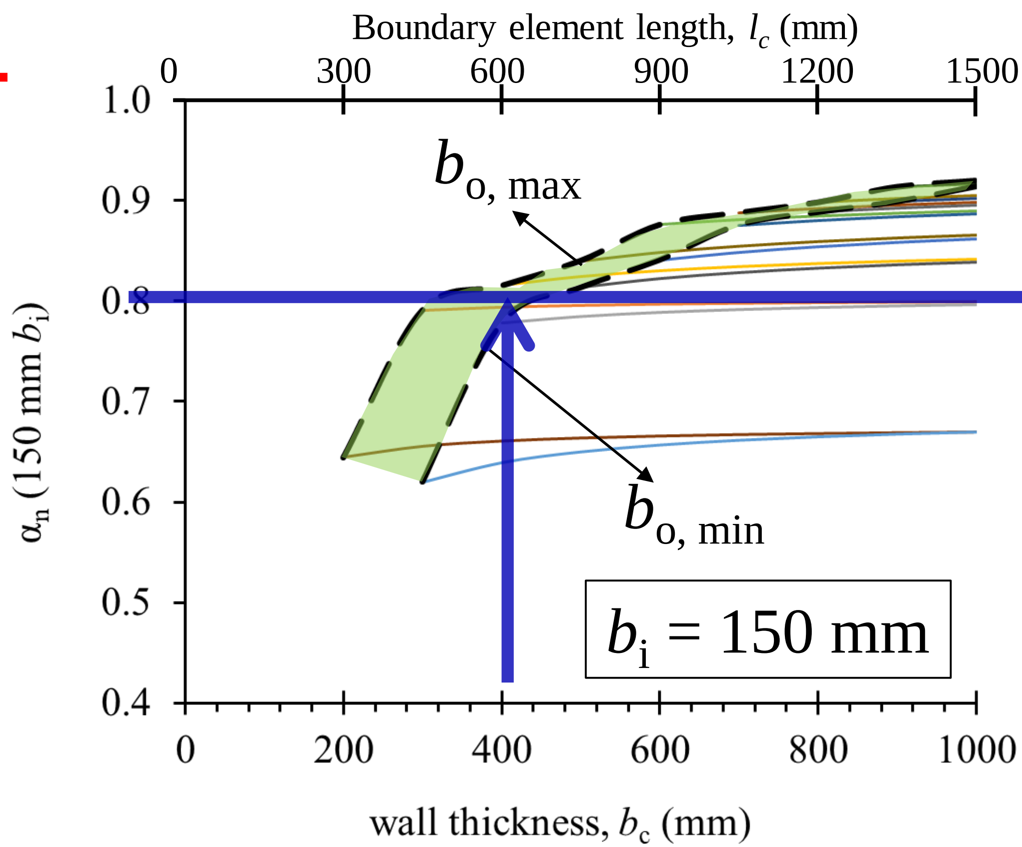
Simplified ductile detailing for RC shear walls

Capacity

Step 3a: α_n

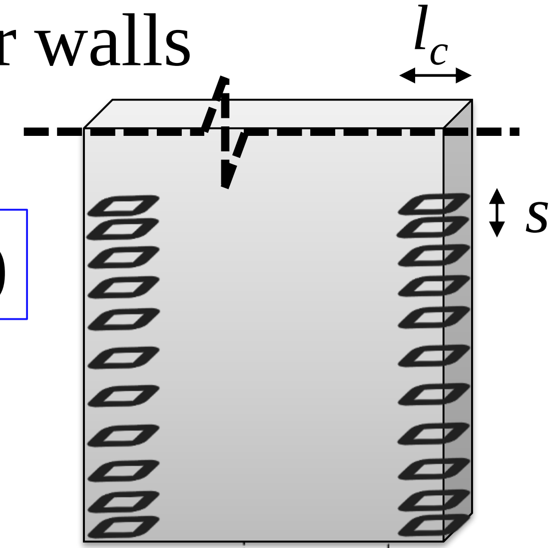
$$\alpha_n = [1 - \sum_i^n (b_i^2 / 6)]$$





Average α_n = 0.80

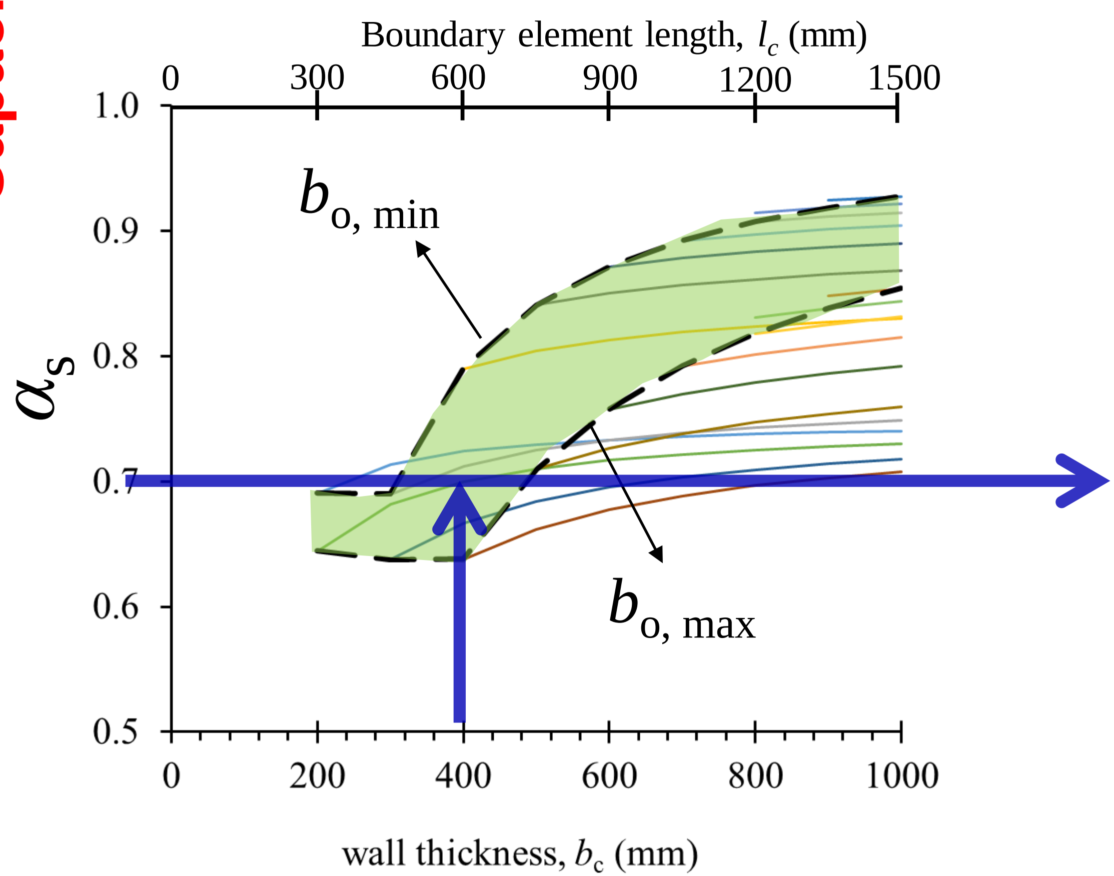
Simplified ductile detailing for RC shear walls

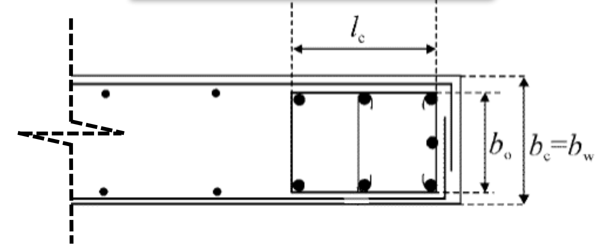


Step 3b: α_s

$$\alpha_s = (1 - s/2b_o)\,(1 - s/2l_c)$$

Capacity





Average α_s = 0.70

Simplified ductile detailing for RC shear walls

Capacity

Step 3c: Capacity (C_c)

Try T12 hoop

$\boldsymbol{f_{yd}/f_{cd}}$ **= 16.3**

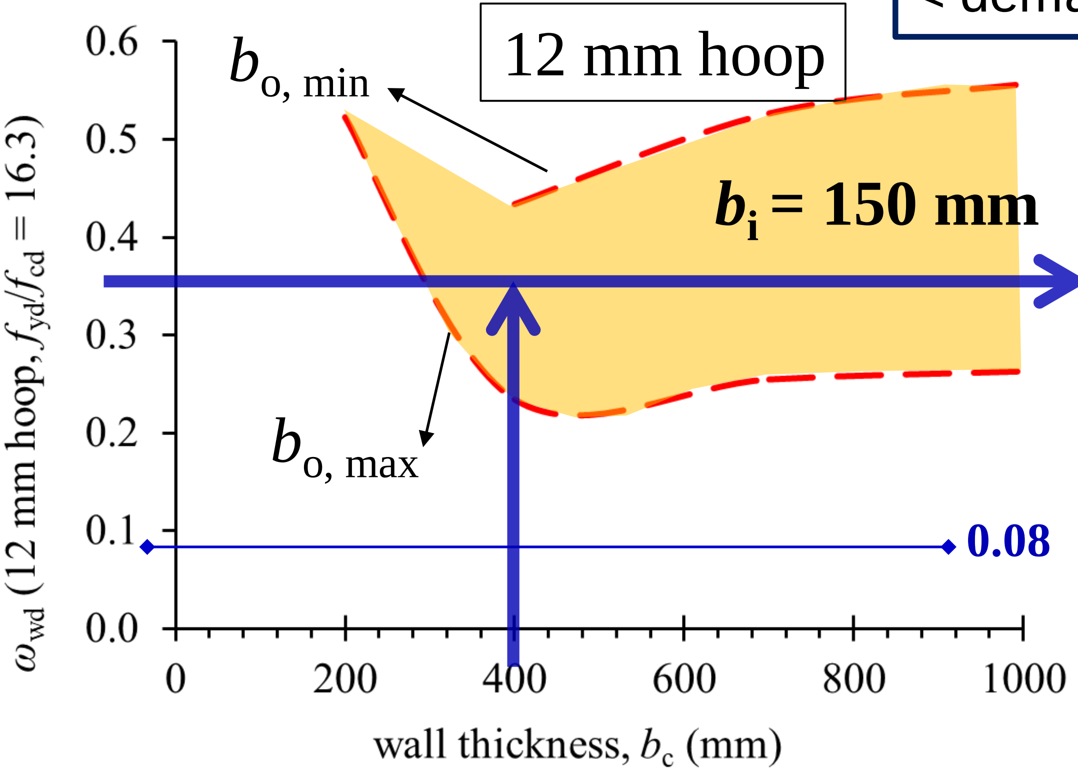
(for f_{yk} = 500 MPa, f_{ckcube} = 50 MPa)

Confinement capacity

$= \alpha_n \, \alpha_s \, \omega_{wd}$

= 0.80 (0.70) (0.35) ≈ 0.20

< demand of 0.35 (Failed!)



Average ω_{wd} = 0.35

Reconciliation

- Hoop spacing (s) and vertical rebar spacing (b_i) of 150 mm is reasonable and makes little sense to decrease them.
- Making shear walls thicker is not ideal.
- Hence, suggest to use 16 mm diameter hoop. (or bundled rebars)

Simplified ductile detailing for RC shear walls

Capacity

Step 3c: Capacity (C_c)

Try T16 hoop

f_{yd}/f_{cd} **= 16.3**

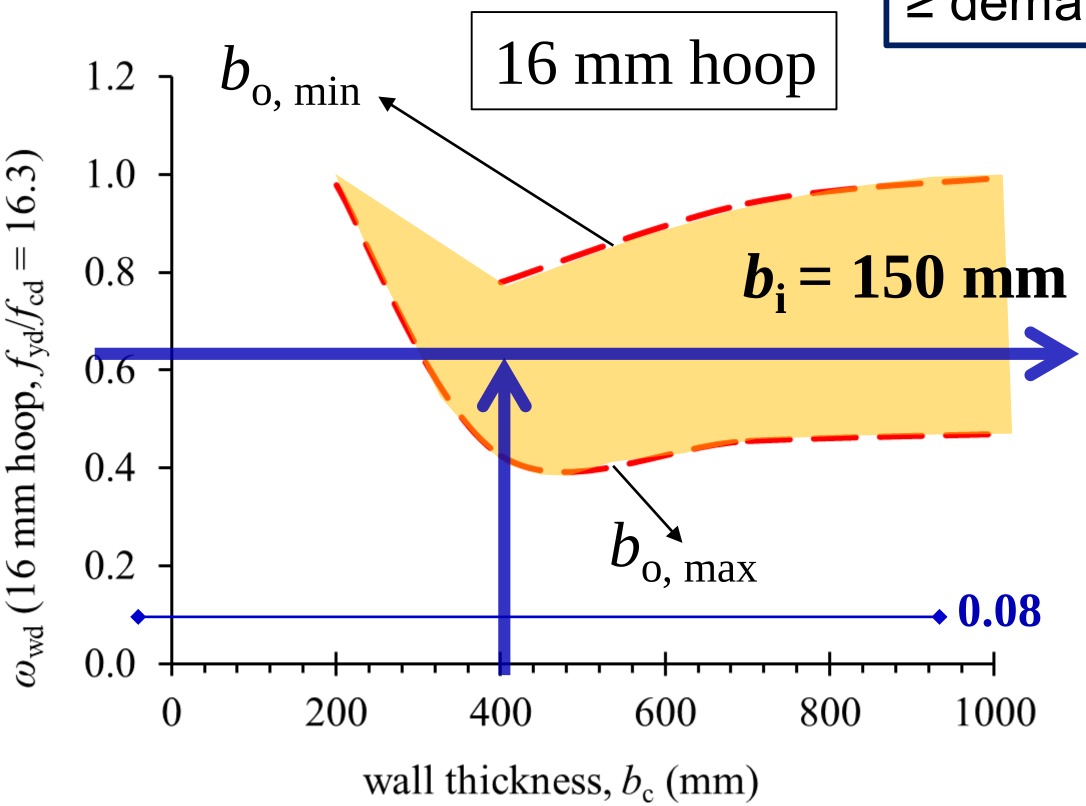
(for f_{yk} = 500 MPa, f_{ckcube} = 50 MPa)

Confinement capacity

$= \alpha_n \, \alpha_s \, \omega_{wd}$

= 0.80 (0.70) (0.63) ≈ 0.352

≥ demand of 0.35 (OK!)



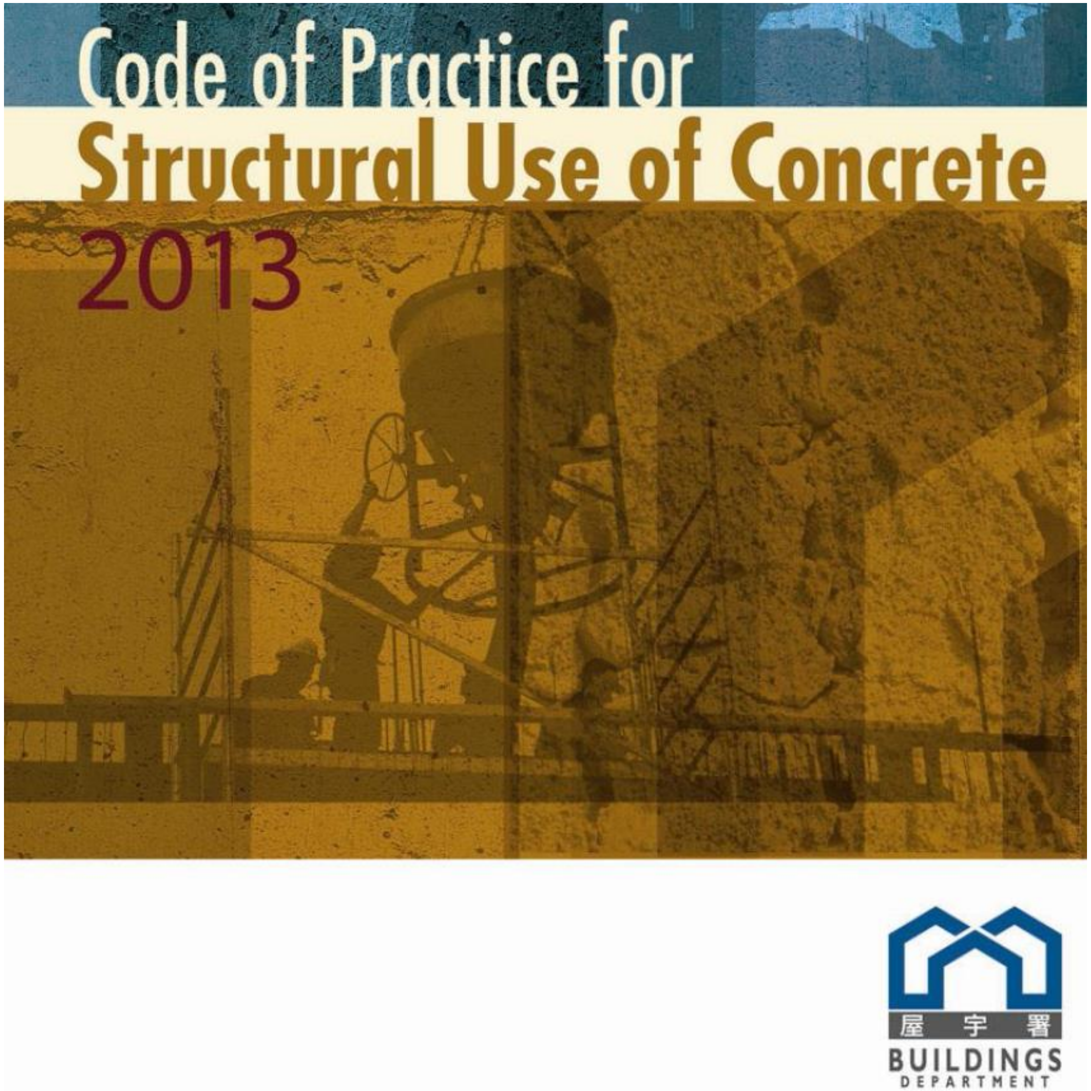
Average ω_{wd} = 0.63

Proposal for a simplified RC wall building

RC wall

- Keep boundary element with dimensions, $A_g \geq$ 400 thickness x 600 length mm^2
- Use hoop rebar diameter, $d_{hoop} \geq 16$ mm
- Use longitudinal rebar diameter, $d_{bL} \geq 20$ mm
- Keep hoop spacing, $s \leq 150$ mm
- Average $\alpha_n = 0.80$
- Average $\alpha_s = 0.70$
- Keep b_i spacing ≤ 150 mm

Corroborate with HK CoP 2013



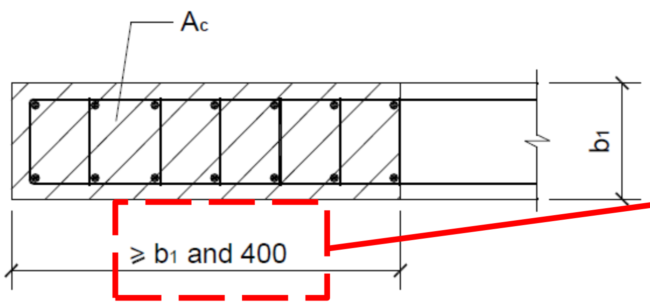
CoP 2013, Cl. 9.9.3.2 for confined boundary elements

For a case of high axial load, $\nu_d = 0.4$

Type	$\rho_{v,be}$ (%)	Vertical rebar diameter (mm)	Hoop diameter (mm)	Hoop vertical spacing (mm)
1	0.6	6 T12	T10	250
2	0.8	6 T16	T10	200
3	1.0	6 T16	T12	150

This study recommends **T20**

This study recommends **T16**



HIDDEN COLUMN

This study recommends 1.5 b_1 with b_1 is 400 mm, hence boundary element length is min. of 600 mm

Content

1. Introduction
2. Curvature ductility demand
3. Tools for simplified shear wall local ductility detailing
4. Proposal for deemed-to-comply simplified solution
5. Limitations and assumptions
6. Conclusion

Limitations and assumptions

- The graphs are developed for wall buildings under EC8 DCM requirement;
- Wall thickness range from 200 to 1000 mm (note that many parameters are extremely sensitive for wall size below 400 mm);
- The cross-sectional aspect ratio is $l_w / b_c \geq 4$ for wall;
- The local ductility demand was based on Class B rebar as per EC2, which is common in Malaysia and Hong Kong;
- The characteristic steel yield strength are for 500 MPa as per Class B in EC2;
- The characteristic concrete cube strength range from 25 MPa to 90 MPa;
- The hoop diameter considered are for 12 mm and 16 mm;
- The hoop spacing (s) and distance (b_i) between consecutive vertical rebar is fixed at 150 mm for practicality.

Content

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Conclusion

1. The motivation of this study is to give engineers guidelines in simplified ductile detailing (if mandated in seismic code);
2. The mysterious confinement detailing equations in EC8 were derived and explained based on Mander et al. (1988);
3. Simplified detailing aid by graphs were presented;
4. Designers are reminded to review the limitations before using the graphs;
5. Proposal was put forward for simplified deemed-to-comply shear walls and compared to HK CoP 2013.

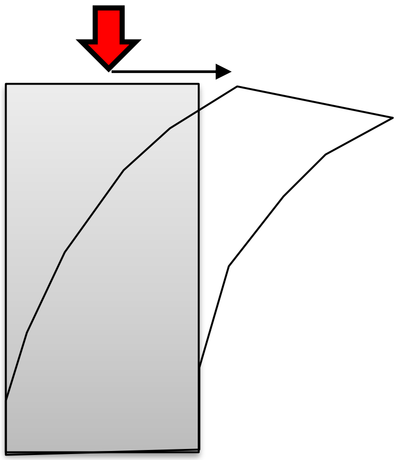
Recommendation: control the axial load ratio

Limiting normalized axial force (v_d)

- $v_d = N_{Ed} / (A_c f_{cd}) \leq 0.40$

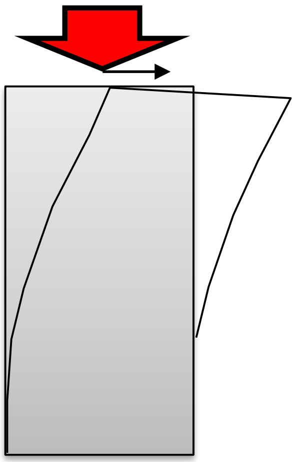
Ultimate vertical load Design cylinder strength

Small v_d



Better deformability

High v_d

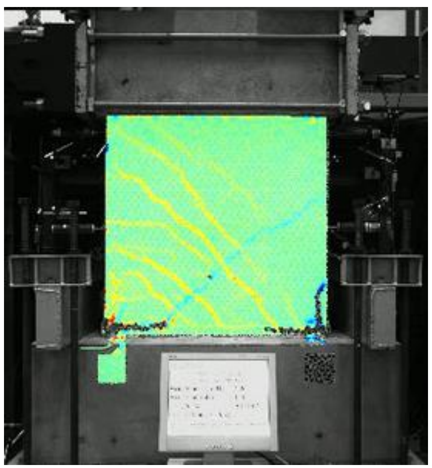


Limited deformability

Tested effects of normalized axial force (v_d) on shear walls

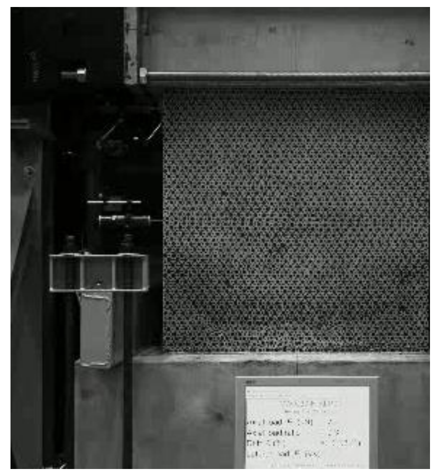
*ALR = $N / (A_c f_{c,mean})$

ALR = 0.1

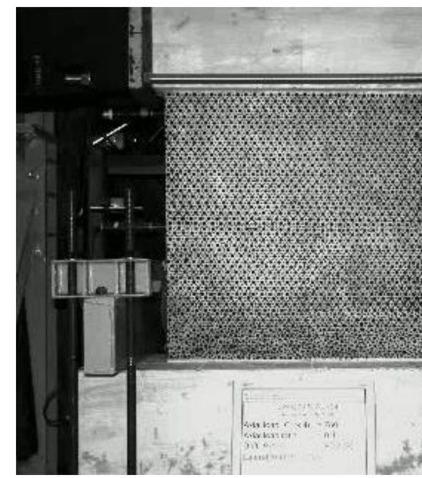


ALR = 0.2

ALR = 0.3



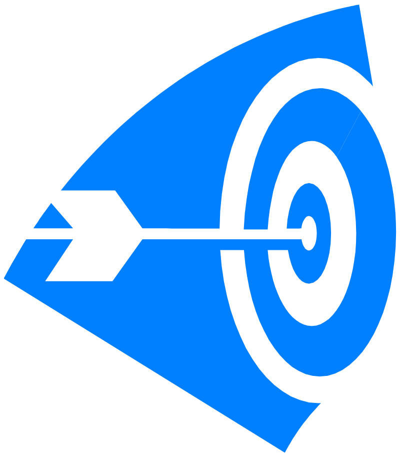
ALR = 0.4



Looi, D.T.W.; Su, R.K.L.; Cheng, B. and Tsang, H.H. (2017). "**Effects of axial load on seismic performance of RC walls with short shear span**", *Engineering Structures*, 115, pp. 312-326.

End of Presentation on

Simplified Shear Wall Detailing in Low-to-moderate Seismicity Regions



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