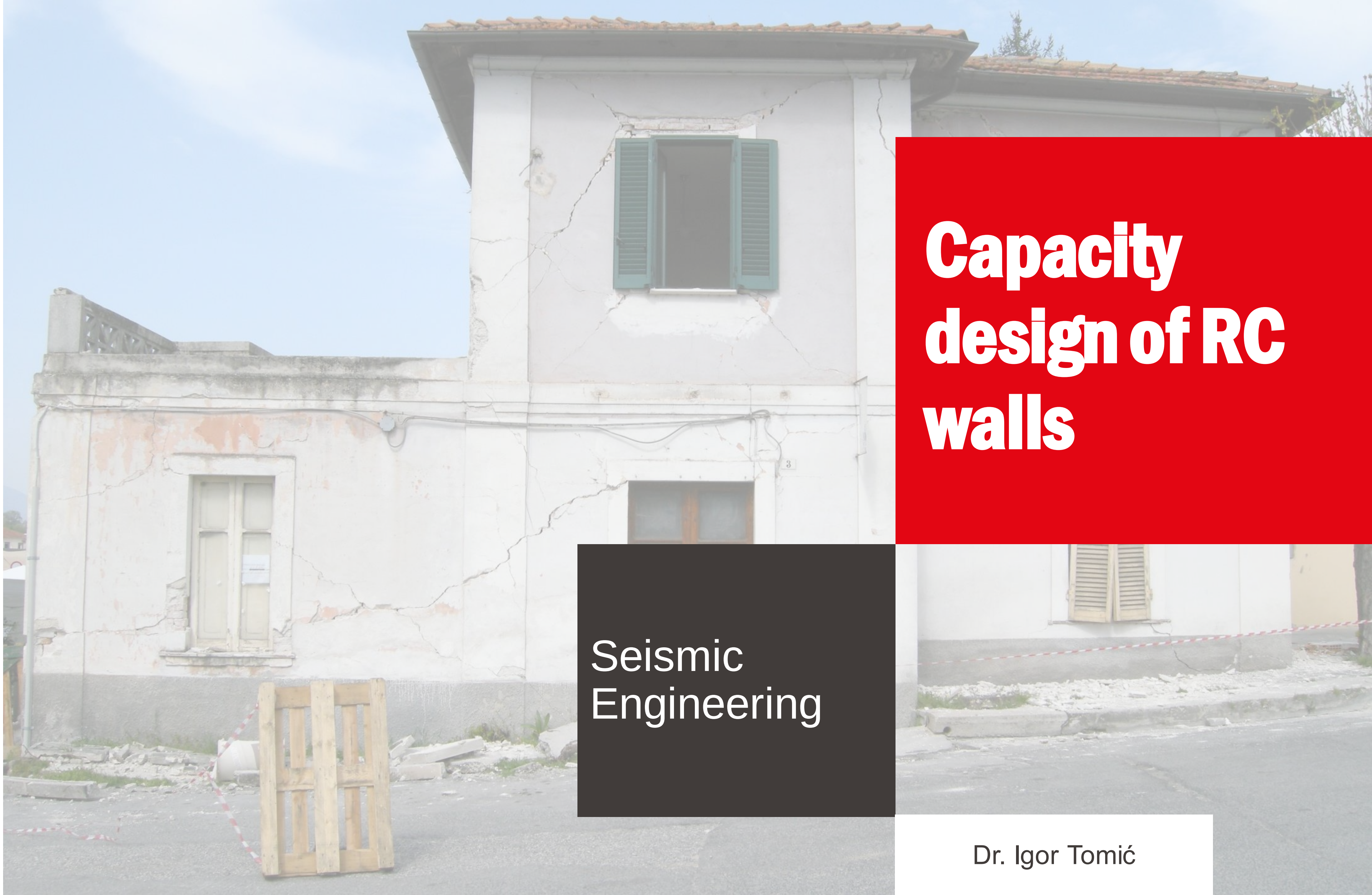
EPFL



Capacity design of RC walls

Seismic Engineering

Dr. Igor Tomić

Capacity design of RC structures

Capacity design (ductile design)

SIA 262 behaviour factors for RC structures:

- Steel class B: q=3.0
- Steel class C: q=4.0

Acier d'armature passive	B500A	B500B	B500C	B700B	Fractile [1]
Produit	Torches, treillis soudés	Barres, torches, treillis soudés	Barres, torches, treillis soudés	Barres, torches, treillis soudés	
Classe de ductilité	A	B	C	B	
Limite d'écoulement f_{sk} [N/mm^2] [2) 3)]	500	500	500	700	5%
Rapport $(f_t/f_s)_k$	≥ 1,05 [4)]	≥ 1,08	≥ 1,15 ≤ 1,35	≥ 1,08	10%
Allongement sous charge ultime ε_{uk} [%]	≥ 2,5 [4)]	≥ 5,0	≥ 7,5	≥ 5,0	10%
Essai de fatigue Contrainte supérieure [N/mm^2] Amplitude de charge [N/mm^2]	300 Barres, torches : 150 [5)]; treillis soudés : 100				10%
Essai de cisaillement pour les treillis, force [kN]	$A_s \cdot 150$ N/mm^2				5%
Ecart maximal par rapport aux dimensions nominales [%]	± 4,5 pour Ø > 8 mm ± 6,0 pour Ø ≤ 8 mm				
Surface	nervurée à ailettes				
Surface projetée relative des nervures f_R [–] 5 mm < Ø ≤ 6 mm 6,5 mm < Ø ≤ 12 mm Ø > 12 mm	 0,035 0,040 0,056				

1) Fractiles pour un seuil de confiance de 90%
2) La valeur maximale déterminée par des essais ne doit pas être supérieure à 1,3 f_{sk}
3) Les aciers d'armature passive avec des résistances plus hautes sont déclarés dans le Registre des aciers d'armature passive conformes aux normes
4) Pour les barres Ø < 6 mm il faut : $(f_t/f_s)_k \geq 1{,}03$ et $\varepsilon_{uk} \geq 2{,}0\%$
5) Pour les barres 20 mm < Ø ≤ 40 mm : 135 N/mm^2

Ductility classes of reinforcement bars (SIA 262(2013))

Capacity design

Capacity design of RC walls in 10 steps

Plastic zone

Point 1: Choice of the plastic mechanism and the height of the plastic zone.

Point 2: Flexural design of the plastic zone.

Point 3: Check stability of the wall in the plastic zone.

Point 4: Ensure that the curvature ductility of the plastic zone is sufficient.

Point 5: Stabilise the longitudinal reinforcement of the plastic zone.

Point 6: Shear design of the plastic zone.

Elastic region

Point 7: Flexural design of the elastic region.

Point 8: Shear design of the elastic region.

Point 9: Stabilise longitudinal reinforcement of the elastic zone.

Point 10: Check the foundation.

@P. Lestuzzi

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→ Here we follow the principles of the Swiss code.

Capacity design

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@P. Lestuzzi

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Capacity design

Point 1: Choice of the plastic mechanism and of the height of the plastic zone

Check slenderness: $h_w / l_w \geq 2.0$

Check axial load ratio: $-N / A_c f_{cd} \leq 0.4$

Mechanism for slender RC walls: Plastic hinge at the base

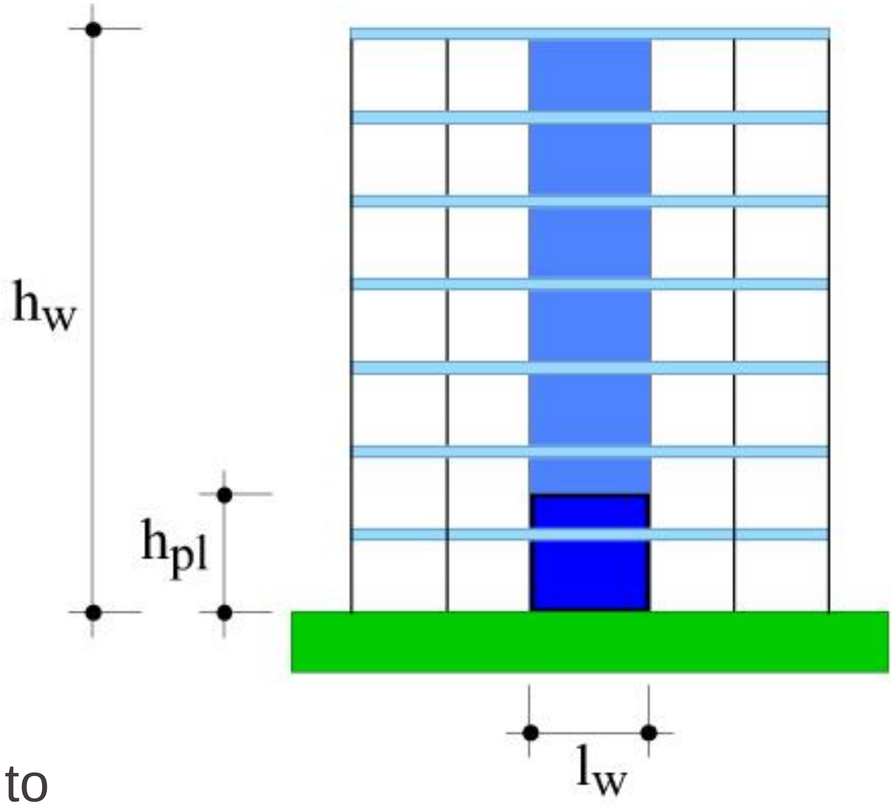
Height of the plastic zone h_{pl}:

if $h_s < \max(2l_w/3, h_w/9)$: $h_{pl} \geq \max(l_w, h_w/6)$

if $h_s \geq \max(2l_w/3, h_w/9)$: $h_{pl} = h_s$

h_s= Height of the first storey

In plastic zone: Special detailing requirements to ensure sufficient curvature capacity.
No openings in the plastic zone!



@P. Lestuzzi

Capacity design

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Capacity design

Point 2: Flexural design of the plastic zone

Design for flexure:

$$M_{Rd} \geq M_d$$

M_{Rd} = Flexural resistance

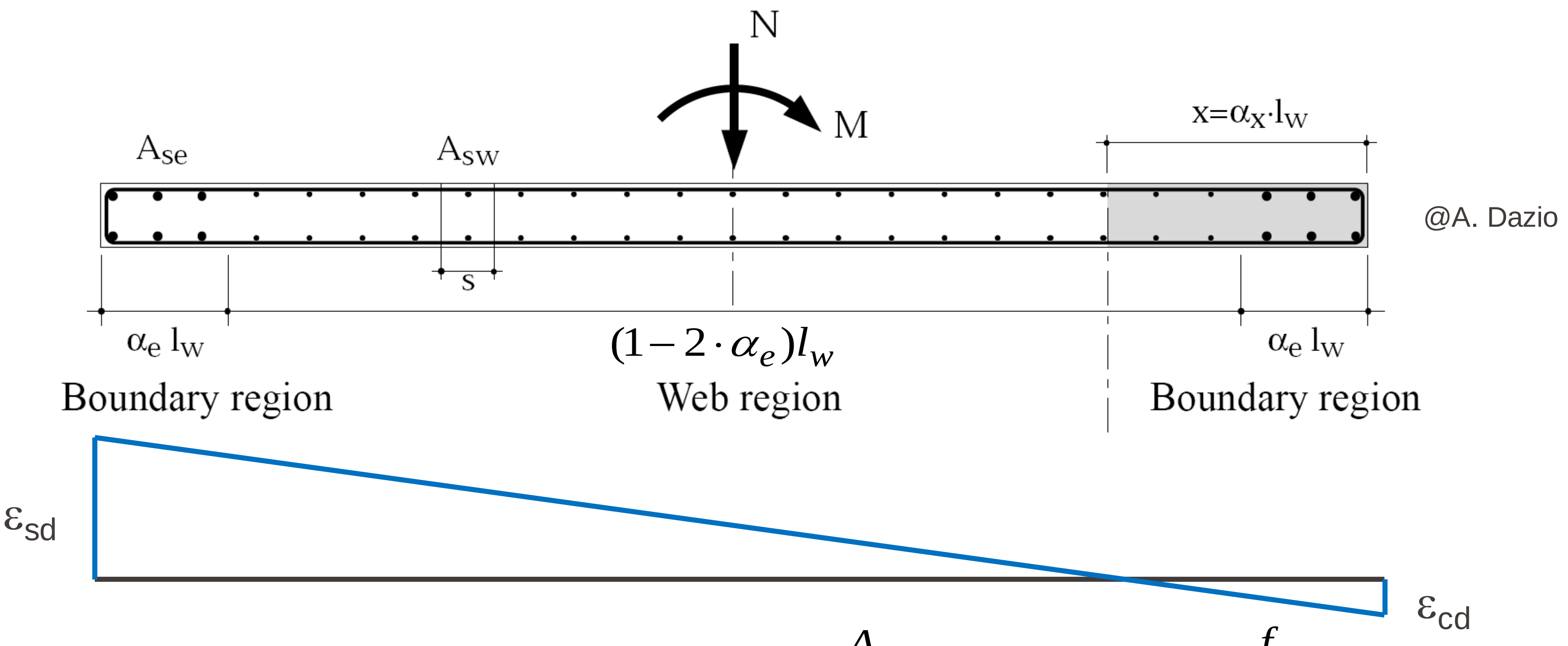
M_d = Design moment (e.g. from ELF method)

→ Use section analysis programs or hand calculations to determine the flexural resistance of a section.

Capacity design

Dr. Igor Tomić

Flexural resistance of a wall:



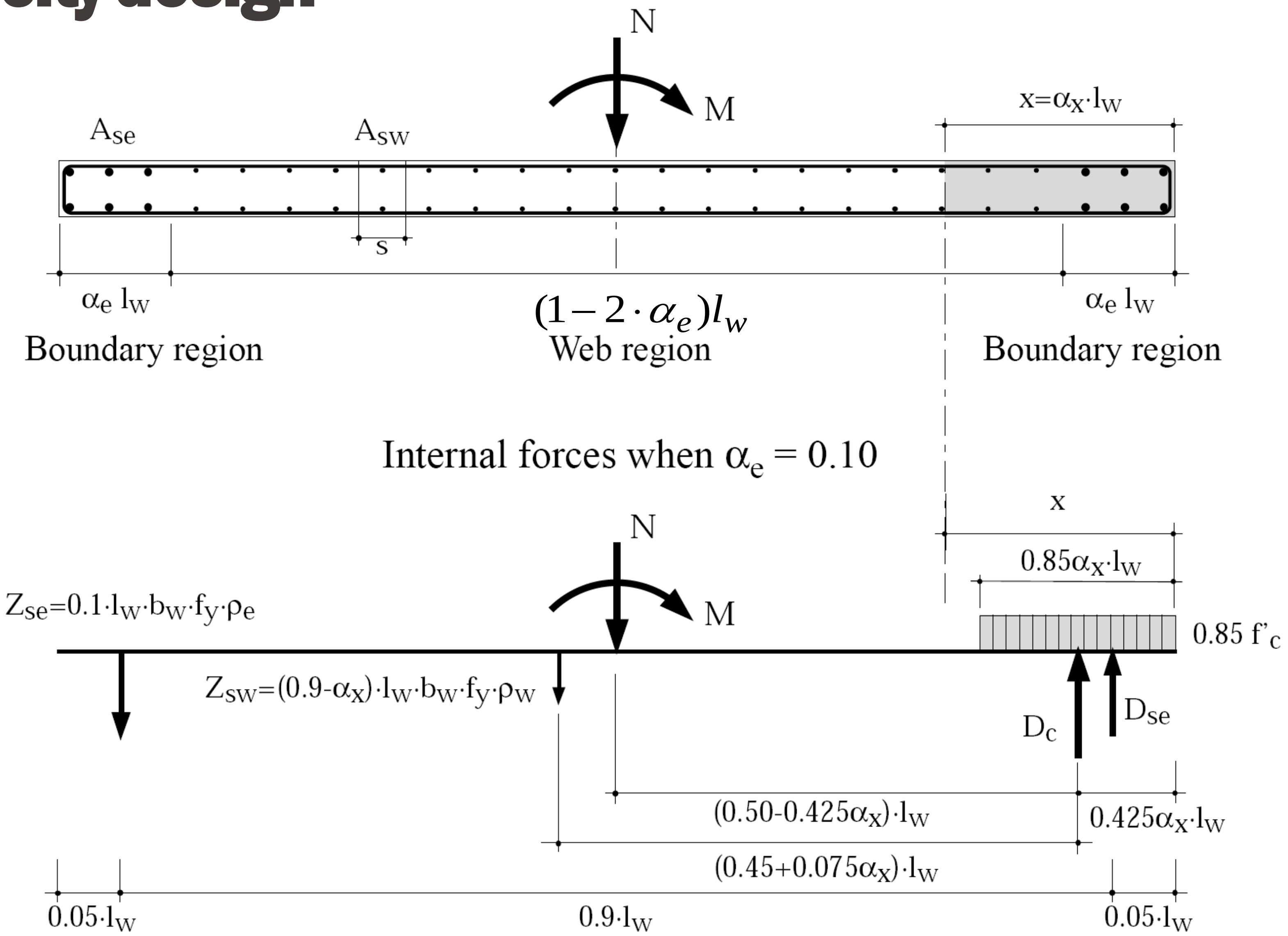
@A. Dazio

Total reinf. content $\rho_t = \frac{A_{s,tot}}{b_w l_w}$ $\omega_t = \rho_t \frac{f_s}{f_c}$

Reinf. content of the web $\rho_w = \frac{A_{sw}}{b_w s}$ $\omega_w = \rho_w \frac{f_s}{f_c}$

Reinf. content of the boundary element $\rho_e = \frac{A_{se}}{\alpha_e b_w l_w}$ $\omega_e = \rho_e \frac{f_s}{f_c}$

Capacity design



@A. Dazio

Capacity design

Assumptions:

- Steel: elasto-plastic stress-strain relationship
- Boundary elements: Bars in tension and compression are considered
- Web: Only the bars in tension are considered
- Concrete: tensile strength is neglected, in compression: « equivalent stress block »

- Axial load ratio $$\nu = \frac{N}{l_w b_w f_c}$$
- Normalised compression zone depth $$\alpha_x = \frac{\nu + (1-\alpha_e)\varpi_w}{0.85^2 + \varpi_w}$$
- Flexural capacity:

$$m = \frac{M}{{l_w}^2 b_w f_c} = \left(\frac{1-\alpha_e}{2}\right)\varpi_t + (0.5 - 0.425\alpha_x)\nu +$$

$$\left[\left(\frac{\alpha_e - \alpha_e^2}{2}\right) + 0.425(\alpha_e - 1)\alpha_x - 0.075\alpha_x^2\right]\varpi_w$$

Capacity design

SIA 262 (2013): Detailing of the longitudinal reinforcement in the plastic zone:

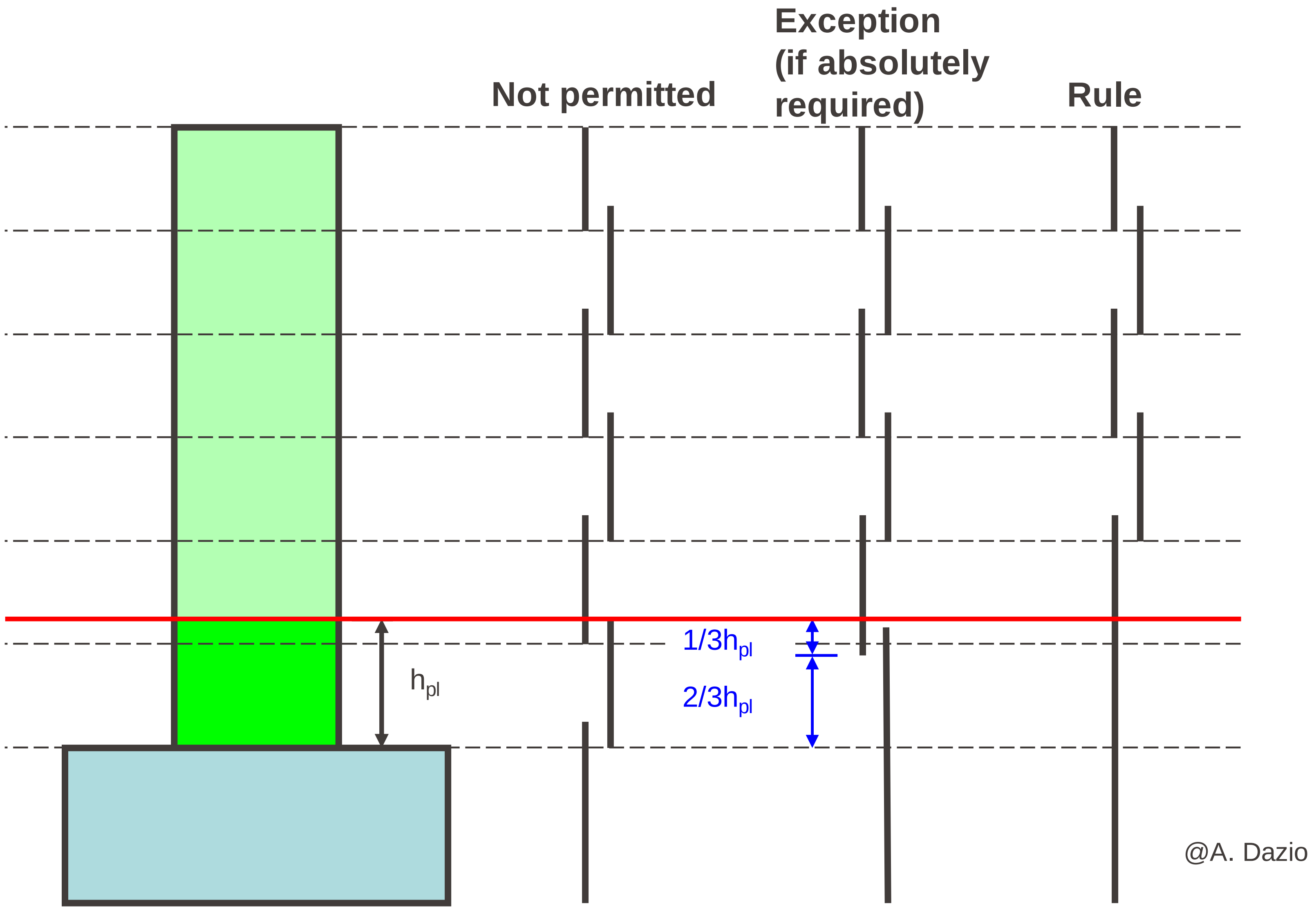
- Avoid lap splices in the plastic zone!
- Limit max. distance between 2 longitudinal bars:

  $s \leq \min(250\ \text{mm},\ 25\ \Phi)$
- Lower and upper bound limit for the longitudinal reinforcement content of the web and boundary elements: $0.3\% \leq \rho_e \leq 3.0\%$

Capacity design

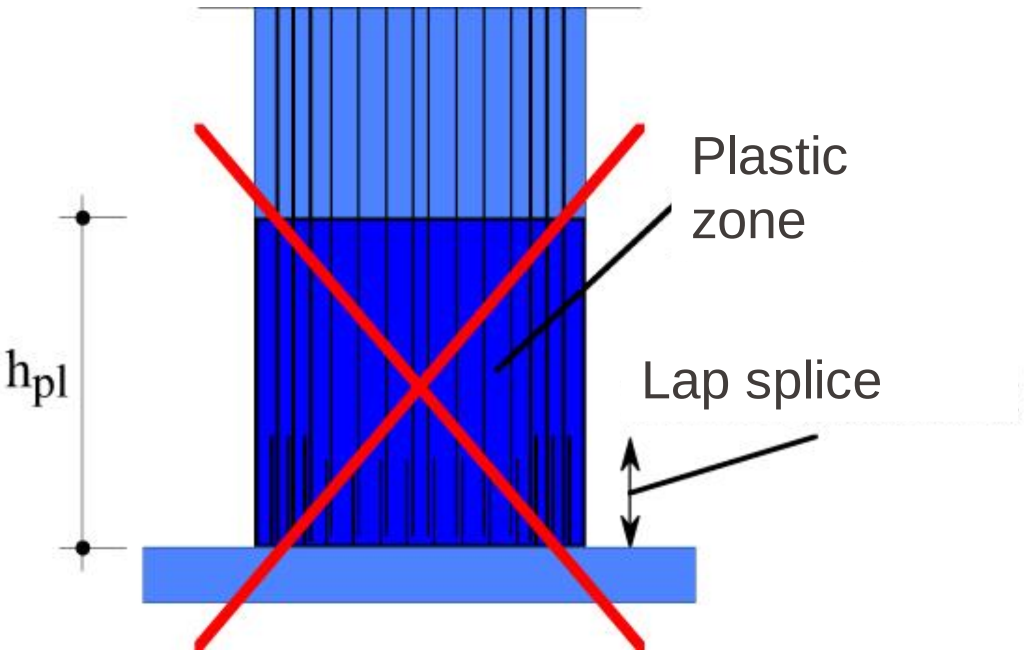
Dr. Igor Tomić

SIA 262: Splicing of longitudinal reinforcement bars



Capacity design

Lap splices in the plastic zone



@ P. Lestuzzi

@ P. Lestuzzi

Capacity design

Capacity design of RC walls in 10 steps

Plastic zone

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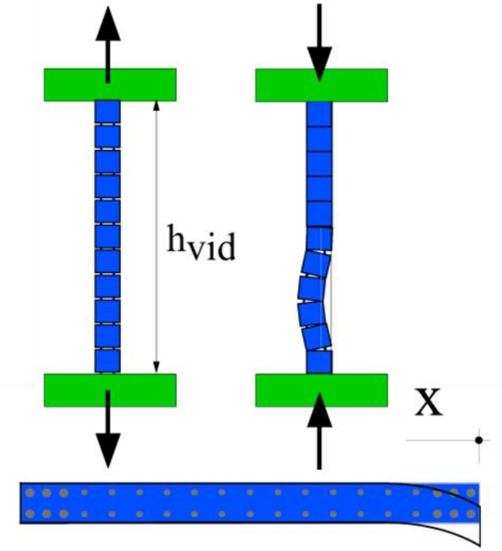
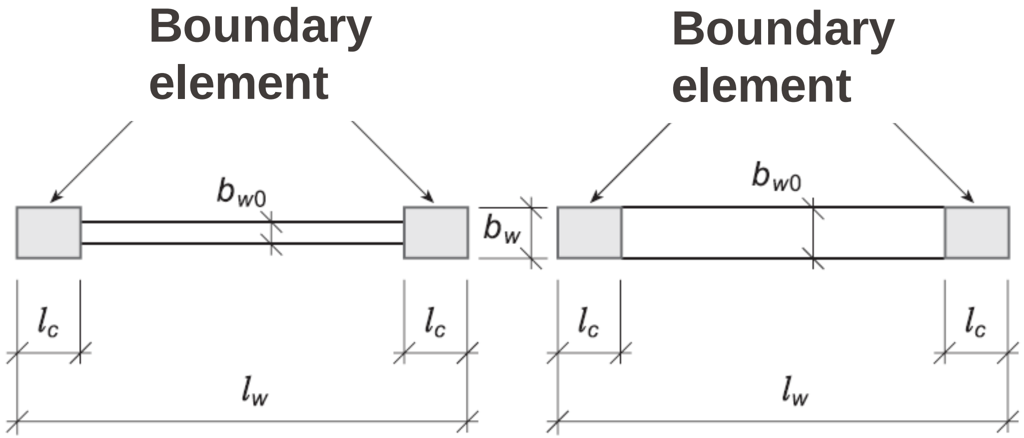
Capacity design

Point 3: Check stability of the wall in the plastic zone





Avoid buckling of the boundary element in compression:

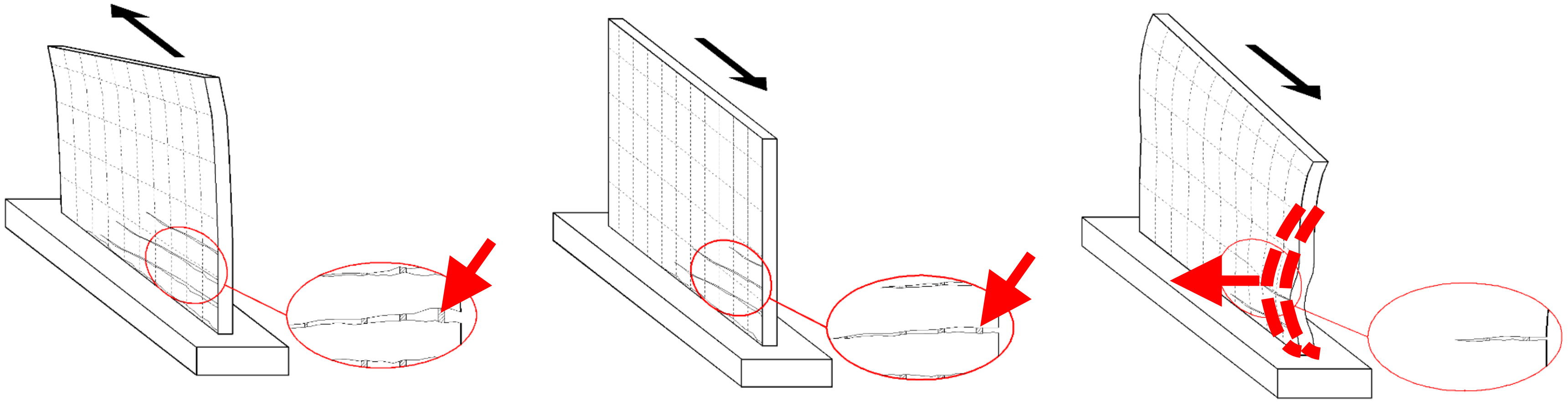
Width of the boundary element: $b_w \geq \max(200\text{ mm}, h_s/15)$
Length of the boundary element: $l_c \geq \max(300\text{ mm}, l_w/10, 0.7c)$
Width of the web: $b_{w0} \geq \max(150\text{ mm}, l_w/25, h_s/20)$

h_s = First storey height
c = Depth of the compression zone

Capacity design

Out-of-plane instability of thin walls

What is the mechanism behind out-of-plane instability?



Rosso et al. (2017): Out-of-plane stability of wall boundary elements with a single layer of vertical reinforcement

Video: Out-of-plane cycle with recovery

Video: Out-of-plane cycle leading to failure

Capacity design

Capacity design of RC walls in 10 steps

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@P. Lestuzzi

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Capacity design

Point 4: Ensure that the curvature ductility of the plastic zone is sufficient

Deformation capacity of the concrete

→ Confinement of the concrete in the compression zone

According to SIA 262:

- SIA 262 does not compute explicitly the deformation capacity (one could, for example, use for this purpose the plastic hinge method → see Week 5).

- SIA 262 assumes that the following displacement ductilities can be obtained
  - q=3 / μ_Δ~2 (B500B, B700B)
  - q=4 / μ_Δ~2.7 (B500C)

  if the detailing guidelines in SIA 262 are applied.

- Justification: The required displacement ductility capacities are relatively small → a simplified approach seems appropriate.

- Only the curvature ductility demand in the plastic zone is estimated from a semi-empirical relationship and used to determine the confinement reinforcement ratio.

Capacity design

SIA 262 / EC8

In the plastic zone, the volumetric ratio of the confinement reinforcement should comply with the following requirement:

$$\omega_c = \frac{\text{Volume of confinement reinf.}}{\text{Volume of confined concrete}} \cdot \frac{f_{sd}}{f_{cd}}$$

$$\omega_c \geq \frac{1}{\alpha_n \alpha_s}\left(30\mu_\phi\left(\frac{-N_d}{A_c f_{cd}} + \omega_v\right)\frac{f_{sd}}{E_s}\frac{b_w}{b_0} - 0.035\right)$$

α_n, α_s	Factors that describe the efficiency of the confinement reinforcement
μ_Φ	Curvature ductility demand for the plastic zone
ω_v	Mechanical reinforcement ratio of the longitudinal reinforcement in the web
N_d	Axial force (Negative if in compression)
A_c	Cross section of the concrete wall
b_w	Width of the boundary element
b_0, h_0	Width and length of the confined area (from centre line to centre line of the stirrups)

Capacity design

- The curvature ductility demand for the plastic zone can be estimated as:

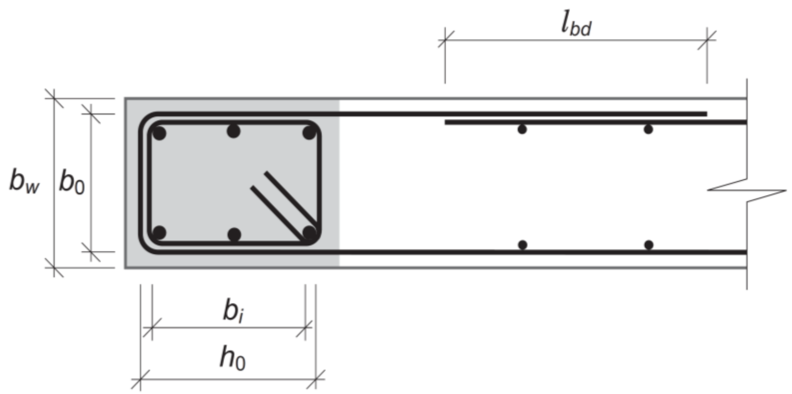
$$T_1 \geq T_C: \quad \mu_\phi = 2q - 1$$

$$T_1 < T_C: \quad \mu_\phi = 1 + 2(q-1)\frac{T_C}{T_1}$$

- Factors that describe the efficiency of the confinement reinforcement:

$$\alpha_n = 1 - \sum_n \frac{b_i^2}{6 b_0 h_0}$$

$$\alpha_s = \left(1 - \frac{s}{2b_0}\right) \cdot \left(1 - \frac{s}{2h_0}\right)$$



b_0, h_0	Width and length of the confined area (from centre line to centre line of the stirrups)
n	Number of longitudinal bars in the confined zone that are stabilised by a hoop or hook.
b_i	Distance between two longitudinal bars that are stabilised by a hoop or a hook.

Capacity design

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Elastic region

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@P. Lestuzzi

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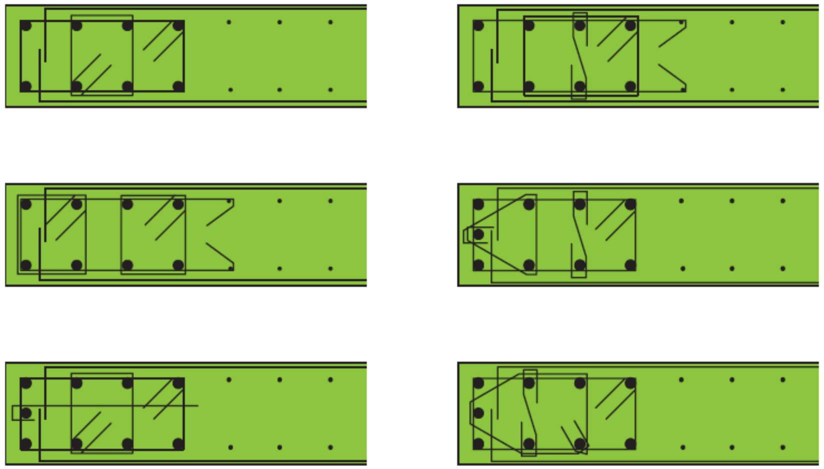
Capacity design

Point 5: Stabilise the longitudinal reinforcement in the plastic zone

- Vertical spacing of hoops: $s \leq \min(150\ \text{mm}, 6\Phi_{sl})$
- Distance between the base of the wall and the first hoop must not exceed 50 mm.
- Diameter of the hoops: $\Phi_e \geq 0.35\Phi_{sl,max}$
- All hoops with 135° hooks!
- At least one longitudinal bar out of two must be stabilised. The distance between stabilised bars must not exceed 200 mm.
- Hoops can stabilise the longitudinal reinforcement and confine the concrete at the same time.

Capacity design



[SIA02] Bild G.26

Example SIA 262

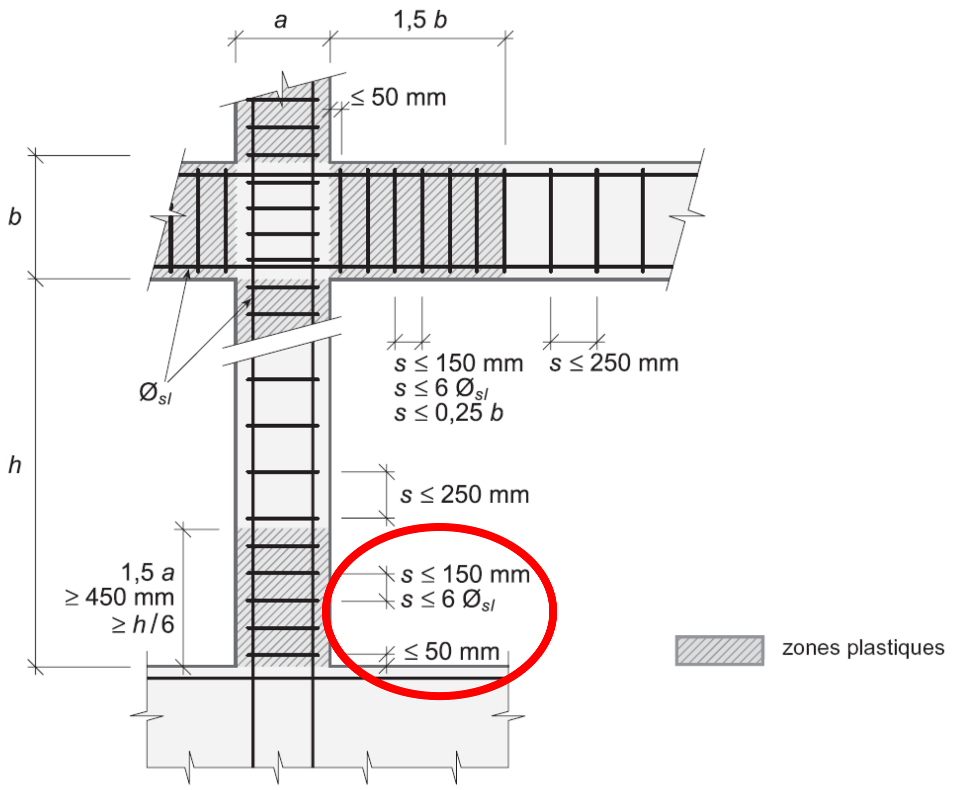
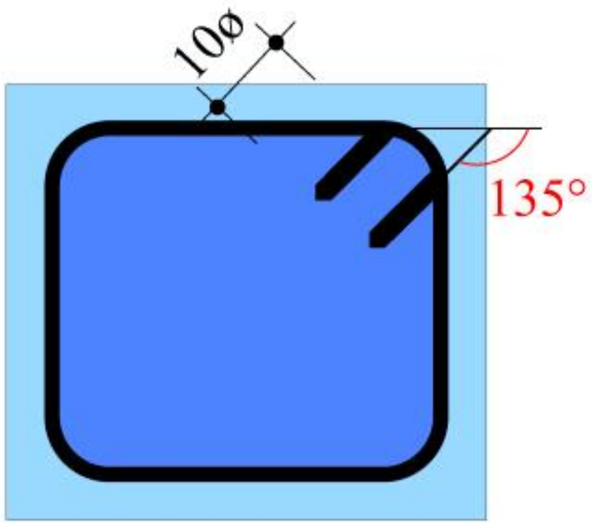


Figure 43: Dispositions constructives pour les poutres et les colonnes

Capacity design

Hoops with 135° hooks



@ P. Lestuzzi

Capacity design

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Capacity design

In order to avoid a brittle failure mode, the resistance associated with the brittle failure modes must be larger than the effective resistance associated with the ductile failure mode.

→ **We need to account for the flexural overstrength in the plastic zone!**

Overstrength ratio

= Effective strength / Strength that is required according to the design

SIA 262: Amplification factor to account for the overstrength:

$$\varepsilon = \frac{M_{Rd}^{+}}{M_d}$$

M_{Rd}^{+} Effective strength = flexural overstrength.

M_d Design bending moment (e.g. from equivalent lateral force method).

Capacity design

Three causes for overstrength:

- Actual reinforcement ratio is typically larger than what would be strictly necessary (the same for steel profiles).

- Material strength is larger than assumed in design (design strength < mean strength).

  Note: Often only the mean strength of the reinforcement and not of the concrete is considered when computing the overstrength. The effect of the concrete strength on the overstrength is often negligible. According to SIA 262 (2013) the mean strength of the reinforcement can be estimated as:

  Class B: $f_{sm}=1.1f_{sk}$

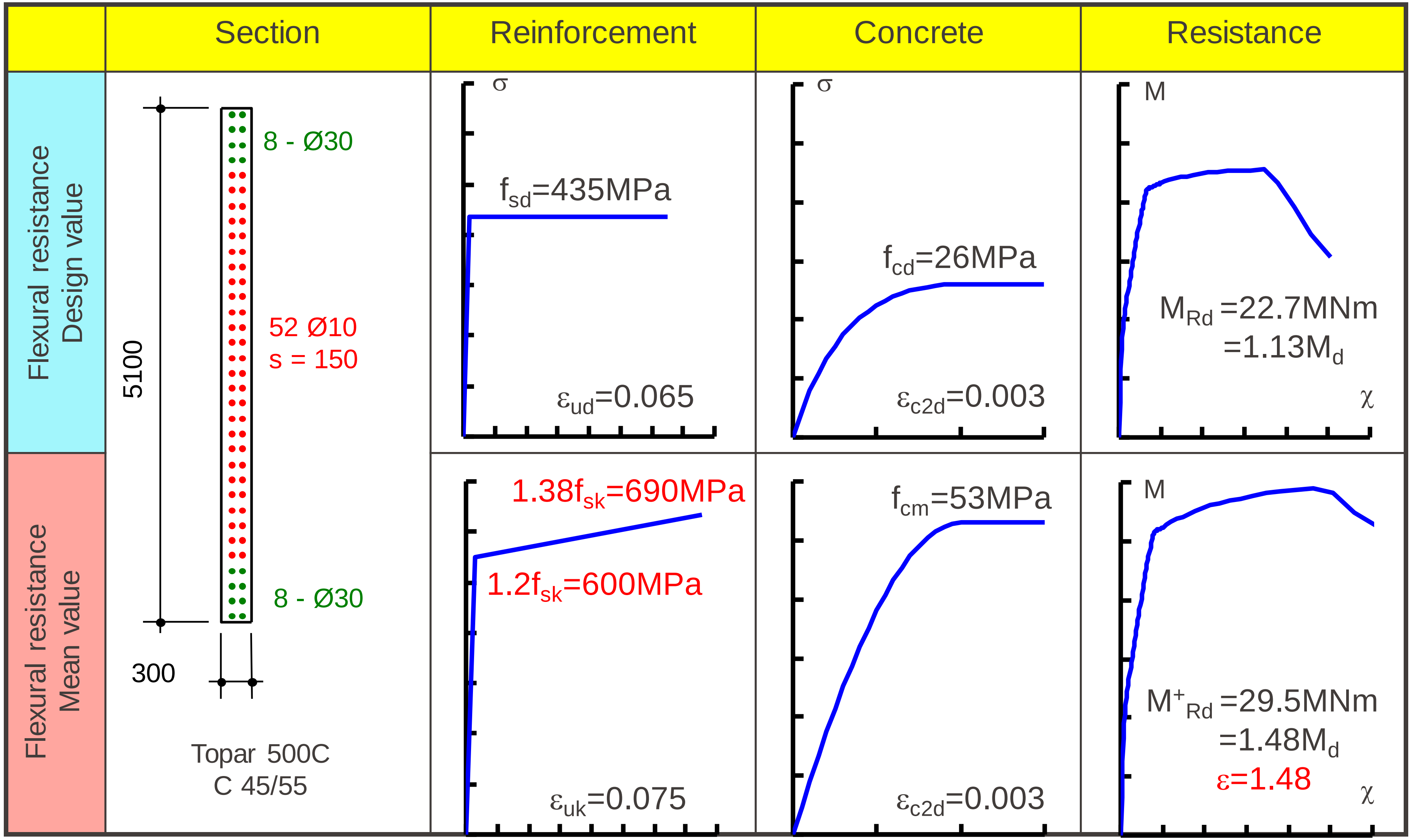
  Class C: $f_{sm}=1.2f_{sk}$

- Plastic redistribution in hyperstatic systems.

Dr. Igor Tomić

Capacity design

Design of a RC wall for M_d=20.0MNm, N_d=3.60MN, V_d=1.37MN



@A. Dazio

Capacity design

Point 6: Shear design of the plastic zone

Conventional design but we account for the flexural overstrength:

$$V_d^+ = \varepsilon \cdot \kappa \cdot V_d$$

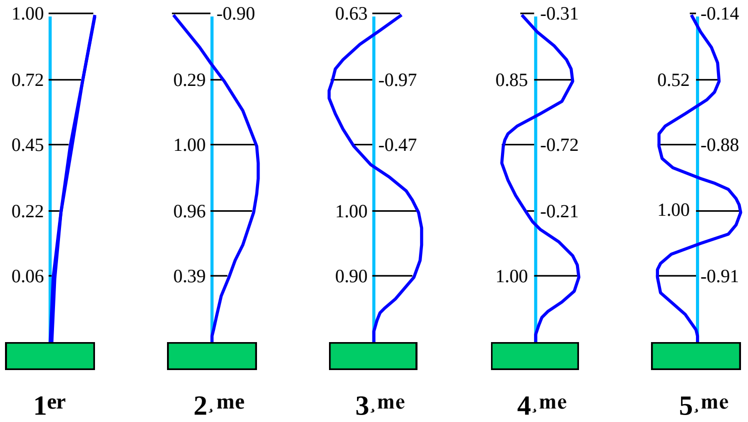
Amplification factor to account for the overstrength:

$$\varepsilon = \frac{M_{Rd}^+}{M_d}$$

Amplification factor to account for higher mode effects (empirical factor):

$$\kappa = 0.9 + \frac{n}{10} \leq 1.5$$

n = Number of storeys



@P. Lestuzzi

One question…

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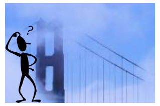
Session ID: cape5



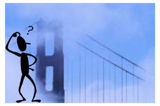
Which of the following statements with regard to the amplification factor M_{Rd}^{+}/M_{d} for the shear design of RC walls is correct?

A. M_{Rd}^{+}/M_{d} is evaluated for the wall section for which V_{d}^{+} is computed.

B. M_{Rd}^{+}/M_{d} is evaluated for all sections and the highest value of the entire wall is considered when computing V_{d}^{+} for any wall section.

C. M_{Rd}^{+}/M_{d} is evaluated for the base section only and this value is considered when computing V_{d}^{+} for any wall section.

One question…



Which of the following statements with regard to V_d^+ is correct?

A. V_d^+ is dependent on the design shear force V_d.

B. V_d^+ is dependent on the design shear force V_d and the moment capacity M_{Rd}^+ at the base of the wall.

C. V_d^+ is dependent on the moment capacity M_{Rd}^+ at the base of the wall but independent of V_d.

D. V_d^+ is dependent on the moment capacity M_{Rd}^+ at the section for which V_d^+ is computed but independent of V_d.

Capacity design

Design for shear

a) Horizontal reinforcement:

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot f_{sd} \cdot z \cdot \cot\alpha \geq V_d^+ \qquad \alpha = 25^o - 45^o \qquad z \cong 0.8 l_w$$

The horizontal reinforcement ratio must be larger than 0.3% and not be less than 25% of the longitudinal reinforcement ratio:

$$\rho_h \geq \max(0.3\%, 0.25\rho_v)$$

b) Compression diagonal

$$V_{Rd,c} = k_c \cdot f_{cd} \cdot b_w \cdot z \cdot \sin\alpha \cdot \cos\alpha \geq V_d^+$$

k_c=0.4 Reduction factor for concrete strength to account for large cracks in plastic zone (SIA 262, 4.2.1.7, 2013).

Capacity design

Dr. Igor Tomić

Capacity design of RC walls in 10 steps

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@P. Lestuzzi

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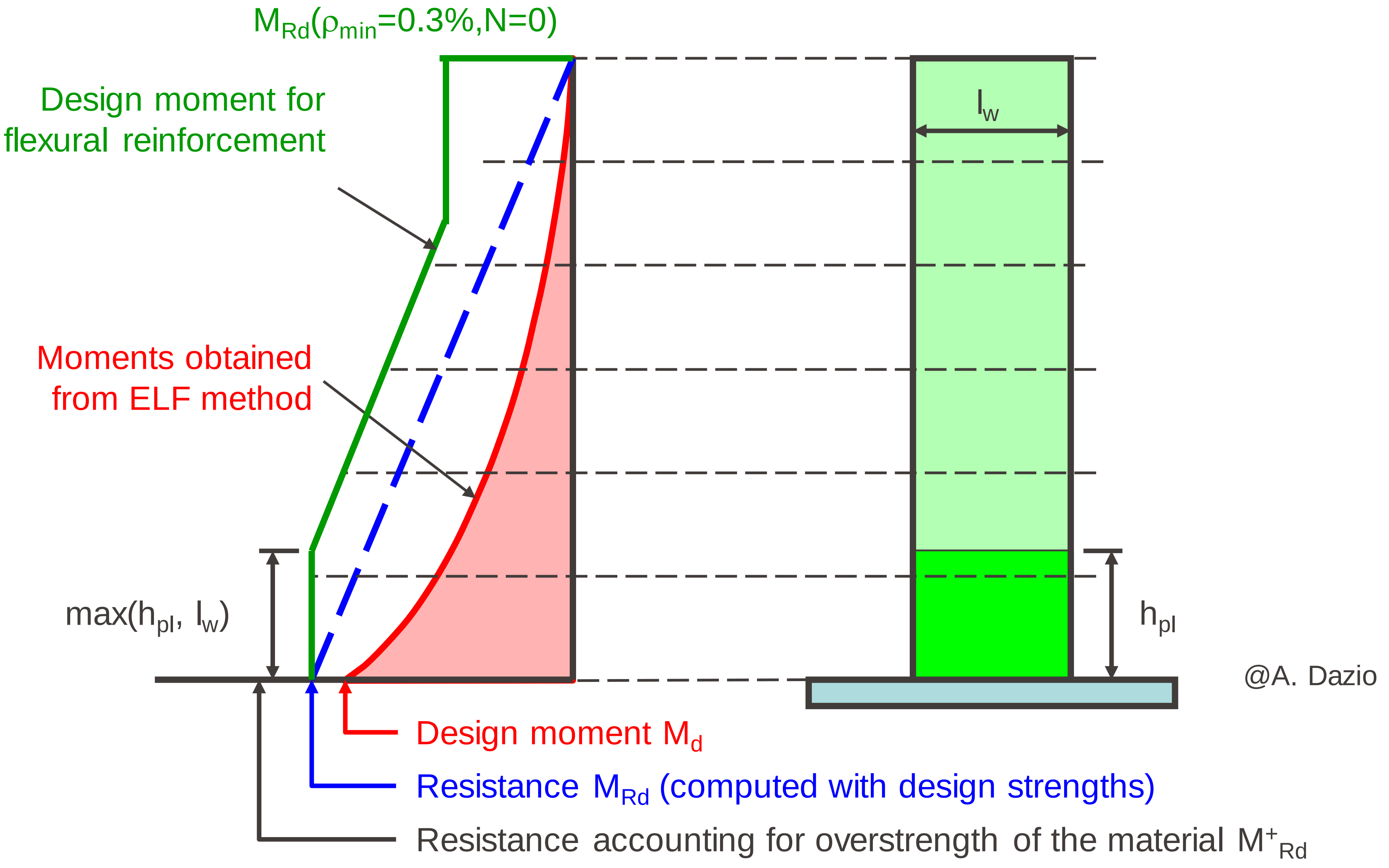
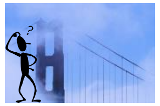
Capacity design

Point 7: Flexural design of the elastic region



One question...



Which of the following statements with regard to the flexural design of the elastic region is correct?

A. The blue line should not be linear but follow the shape of the moments obtained from ELF (red line).

B. The design envelope (green line) is correct.

C. There is an inconsistency in the design procedure. According to capacity design principles, the design envelope (green line) should be based on M_{Rd}^{+} and not on M_{Rd}.

Capacity design

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Capacity design

Point 8: Shear design of the elastic region

Conventional design considering also the amplification due to the flexural overstrength:

$$V_d^+ = \varepsilon \cdot \kappa \cdot V_d$$

Amplification due to the overstrength (this is always the overstrength factor of the section that plastifies, i.e., here the base section):

$$\varepsilon = \frac{M_{Rd}^+}{M_d}$$

Amplification due to the higher mode effects:

$$\kappa = 0.9 + \frac{n}{10} \leq 1.5$$

n = Number of storeys

Capacity design

Design for shear

a) Horizontal reinforcement:

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot f_{sd} \cdot z \cdot \cot\alpha \geq V_d^+ \qquad \alpha = 25^o - 45^o \qquad z \cong 0.8 l_w$$

The horizontal reinforcement ratio must be larger than 0.3% and not be less than 25% of the longitudinal reinforcement ratio: .

$$\rho_h \geq \max(0.3\%, 0.25\rho_v)$$

b) Compression diagonal

$$V_{Rd,c} = k_c \cdot f_{cd} \cdot b_w \cdot z \cdot \sin\alpha \cdot \cos\alpha \geq V_d^+$$

k_c=0.55 Reduction factor for concrete strength to account for small cracks in elastic region (SIA 262, 4.2.1.7, 2013).

Capacity design

Capacity design of RC walls in 10 steps

Plastic zone

Point 1: Choice of the plastic mechanism and the height of the plastic zone.

Point 2: Flexural design of the plastic zone.

Point 3: Check stability of the wall in the plastic zone.

Point 4: Ensure that the curvature ductility of the plastic zone is sufficient.

Point 5: Stabilise the longitudinal reinforcement of the plastic zone.

Point 6: Shear design of the plastic zone.

Elastic region

Point 7: Flexural design of the elastic region.

Point 8: Shear design of the elastic region.

Point 9: Stabilise longitudinal reinforcement of the elastic zone.

Point 10: Check the foundation.

@P. Lestuzzi

→ The step-by-step procedure presented in different codes / references is typically very similar. However, the actual equations to verify the different principles can be quite different.

→ Here we follow the principles of the Swiss code.

Capacity design

Point 9: Stabilisation of the longitudinal reinforcement

<u>In the compression zone:</u>

In order to avoid local buckling of the longitudinal bars, stabilise the corner bars + every other longitudinal bar

- The vertical spacing of the hoops *s* should be limited to:

$$s \leq \min(15\phi_{\min}, a_{\min}, 300mm)$$

- ϕ_{min} Diameter of the smallest longitudinal bar in the compression zone
- a_{min} Minimum dimension of the section (for walls: width)

- Stabilisation is strictly speaking only necessary if concrete spalls – but it is always good practice.

Capacity design

Capacity design of RC walls in 10 steps

Plastic zone

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@P. Lestuzzi

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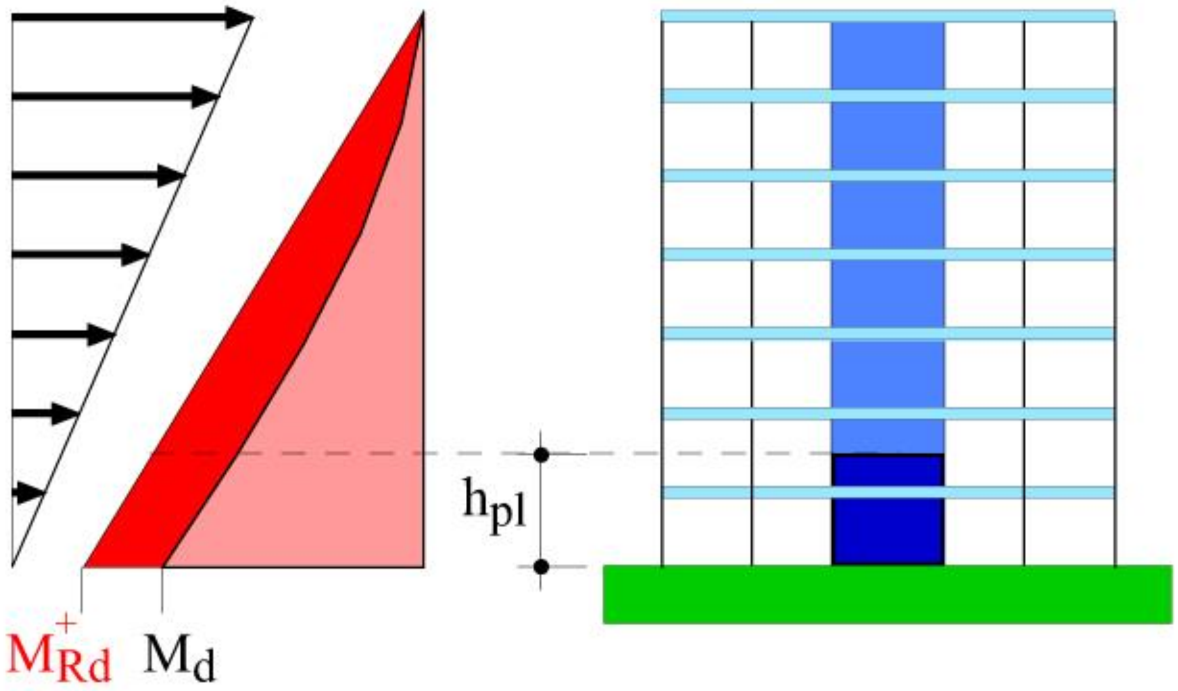
→ Here we follow the principles of the Swiss code.

Capacity design

Point 10: Check the foundation

The foundation needs to be designed to remain elastic considering the overstrength of the plastic zone above the foundation:

M^{+}_{Rd} V^{+}_{d} N_d

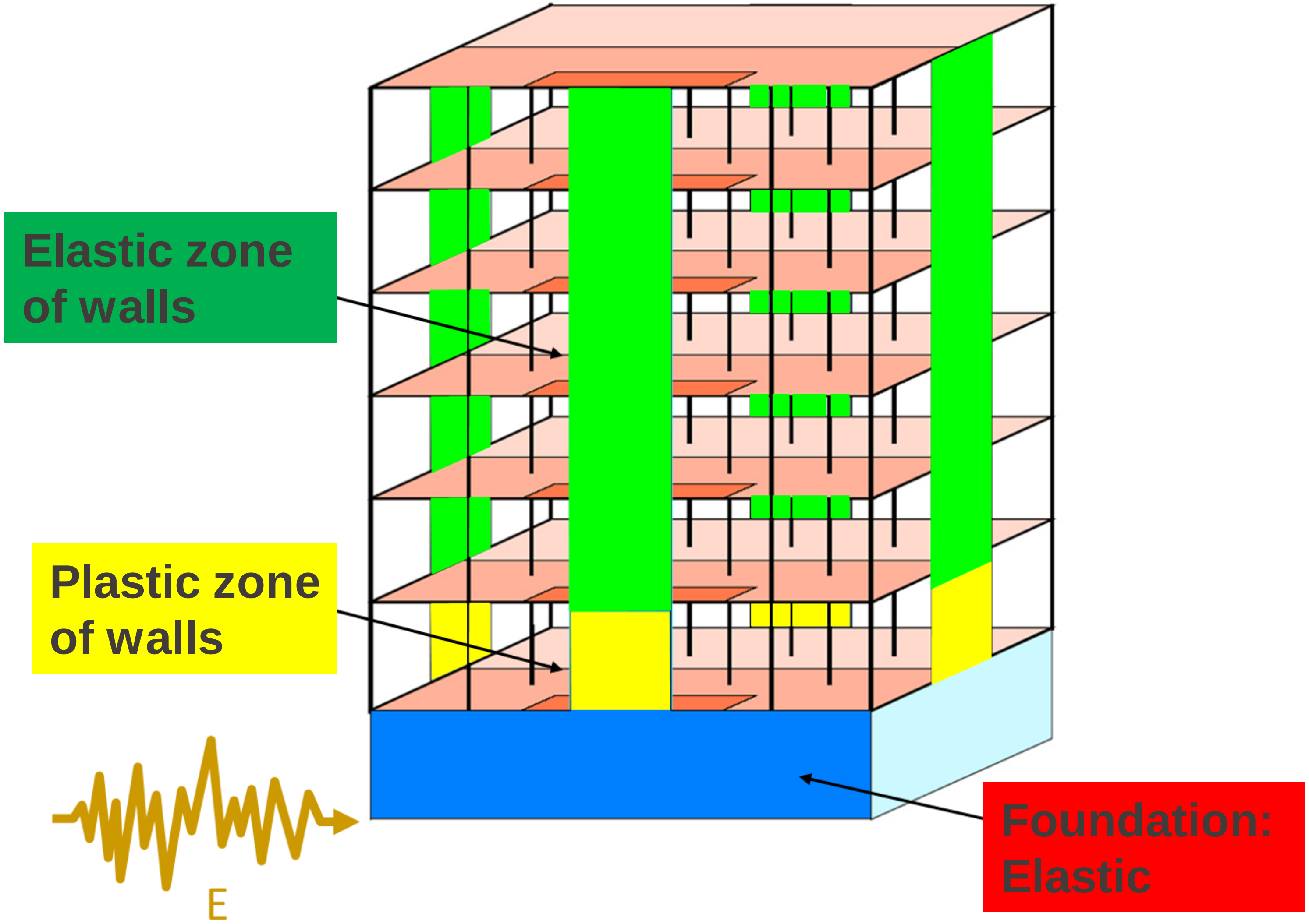


@P. Lestuzzi

Dr. Igor Tomić

Capacity design

Design of a building with slender RC walls



@A. Dazio

Capacity design

Consideration of overstrength in capacity design

1. **Design of flexural capacity of parts that remain elastic above the foundation**

   Design for M_{Rd} (and not M_{Rd}^{+}) because

   i. overstrength due to difference between mean and design material properties will be the same in the section that plastifies and the section that remains elastic;

   ii. a limited plastification in flexure of a section above the plastic hinge does not lead immediately to failure.

   → It would be overly conservative to design for M_{Rd}^{+} .

2. **Design of flexural capacity of foundation**

   Design for M_{Rd}^{+} since it is difficult to inspect and repair the foundation.

3. **Shear design**

   Design for V_d^{+} which is a function of M_{Rd}^{+} . Shear failure needs to be avoided at all costs.

Capacity design

Advantages of capacity design over conventional design:

- A good, robust seismic behaviour is guaranteed.
- The plastic zone has sufficient ductility capacity for a design intensity earthquake (and probably a little more ..).
- Shear failures are excluded (provided our estimate of the dynamic amplification factor was good …).
- The parts around the plastic zones are designed to remain elastic.