Example: Capacity design of a RC wall

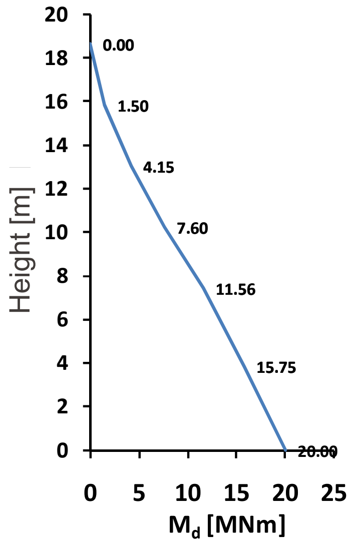
Seismic Engineering

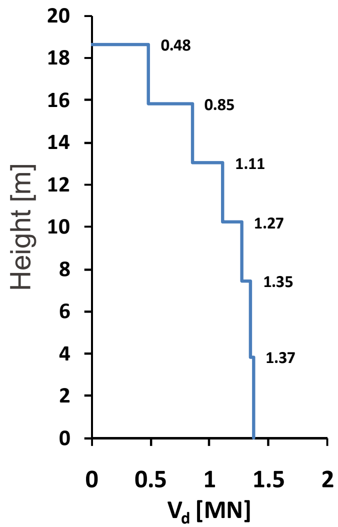
Dr. Francesco Vanin

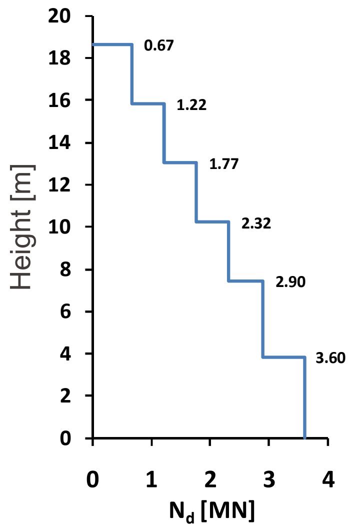
Example: Capacity design

Wall in a 6 storey building (T_1=1.64s)

- Wall: l_w=5.1m, b_w=0.3m
- Height of the first storey: h_s=3.84m
- Height of the building: h=18.63m
- Concrete: C45/55, Steel: S500C (q=4)







Reference: *SIA Dokumentation D 0171: "Erdbebengerechter Entwurf und Kapazitätsbemessung eines Gebäudes mit Stahlbetontragwänden". SIA, Zürich 2002. https://sgeb.ch/userdata/uploads/pdf/dokumentationen/sia-d0171.pdf*

Example: Capacity design

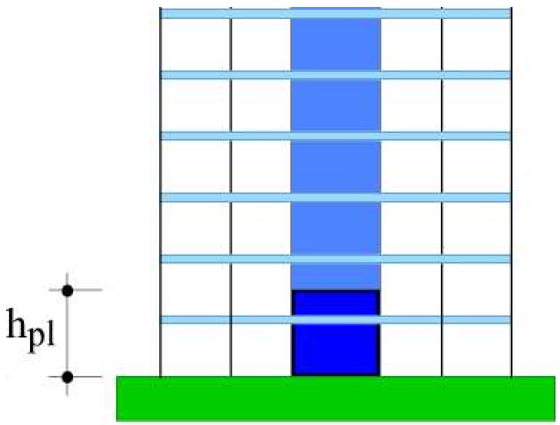
Point 1: Choice of the mechanism and of the height of the plastic zone

Axial force ratio: $$\nu = \frac{3.6MN}{26MPa \cdot 5.1m \cdot 0.3m} = 0.09 < 0.40 \quad ✓$$

Slenderness ratio: $$\frac{h_w}{l_w} = \frac{18.63m}{5.1m} = 3.7 > 2.0 \quad ✓$$

Plastic mechanism: Plastic hinge at the base of the wall

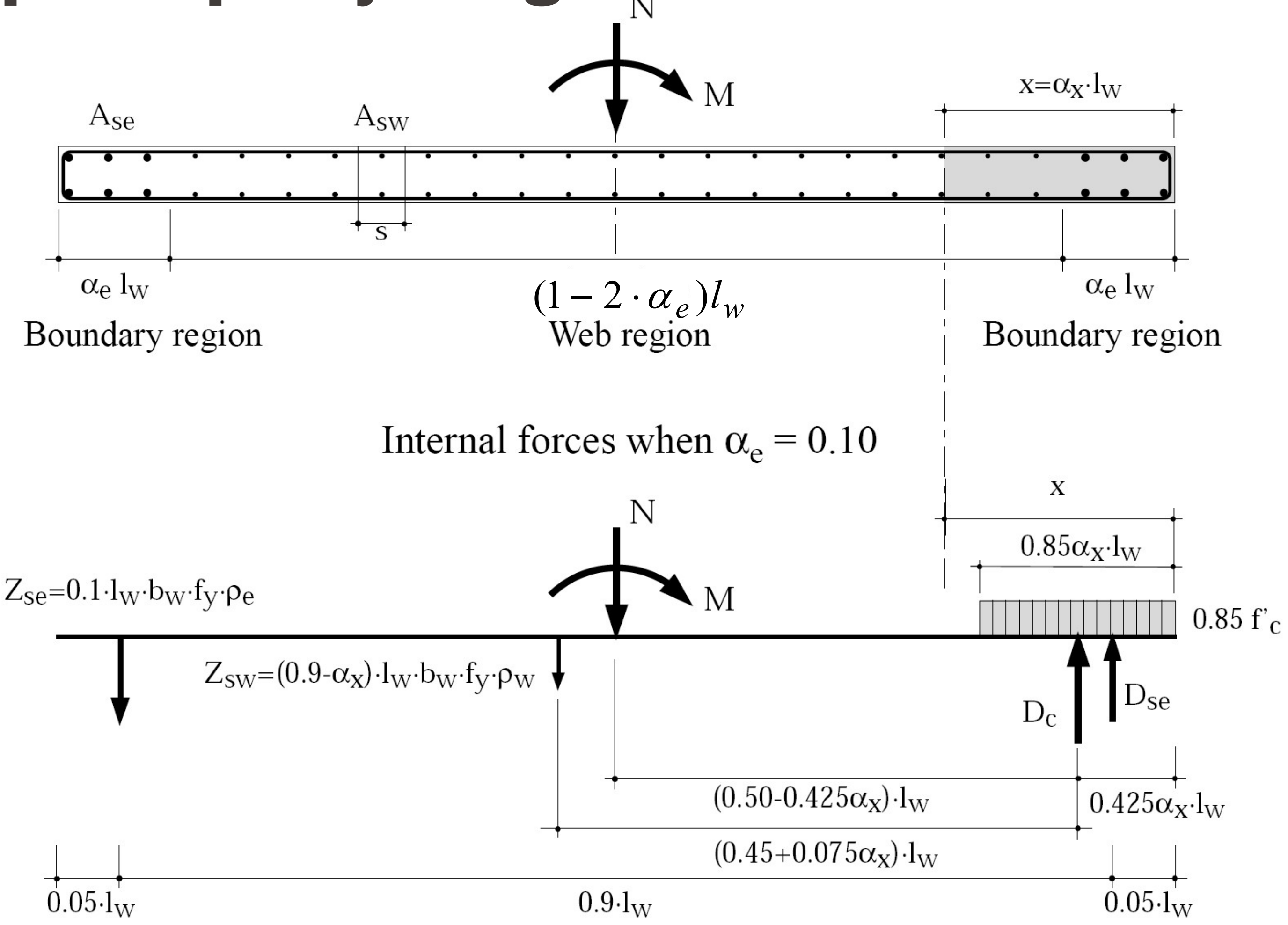
Height of the plastic zone:



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

l_w=5.1m, h_w=18.63m, h_s=3.84m
$h_s \geq \max(3.4m, 2.1m)$: h_{pl} = 3.84m

Example: Capacity design



@A. Dazio

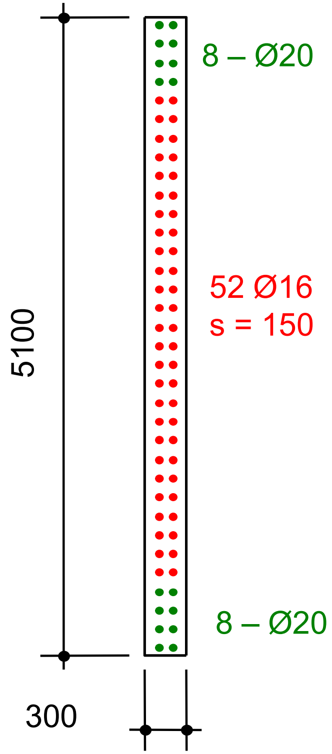
Dr. Francesco Vanin

Example: Capacity design

Point 2: Flexural design of the plastic zone

Design for M_d=20MNm, N_d=3.6MN

Moment resistance of a RC wall (@ A. Dazio)			
	Ø [mm]	Nombre	A_s [mm^2]
Reinf. of each boundary element	20	8	2513
Web reinforcement	16	52	10455
Total reinforcement			15482
		ρ_w [%] =	0.87
α_e [-] =	0.106	ω_w [-] =	0.15
l_w [m] =	5.1	ρ_e [%] =	1.55
b_w [m] =	0.3	ω_e [-] =	0.26
		ρ_t [%] =	1.01
f_y [MPa] =	435	ω_t [-] =	0.17
f_c [MPa] =	26	ν [-] =	0.09
		α_x [-] =	0.25
N_d [kN] =	3600	m [-] =	0.10
M_{Rd} [kNm] =	20967	x [m] =	1.29



Topar 500C
C 45/55

Example: Capacity design

Point 2, continued

SIA 262: Detailing of the longitudinal reinforcement in the plastic zone :

Boundary element:

- $0.3\% \leq \rho_e \leq 3.0\%$: $\rho_e = 1.55\%$ ✓
- $s \leq \min(250\text{mm}, 25\Phi = 500\text{mm})$: $s = 150\text{mm}$ ✓

Web:

- $0.3\% \leq \rho_e \leq 3.0\%$: $\rho_w = 0.89\%$ ✓
- $s \leq \min(250\text{mm}, 25\Phi = 400\text{ mm})$: $s = 150\text{mm}$ ✓

Example: Capacity design

Point 3: Stability of the wall in the plastic zone

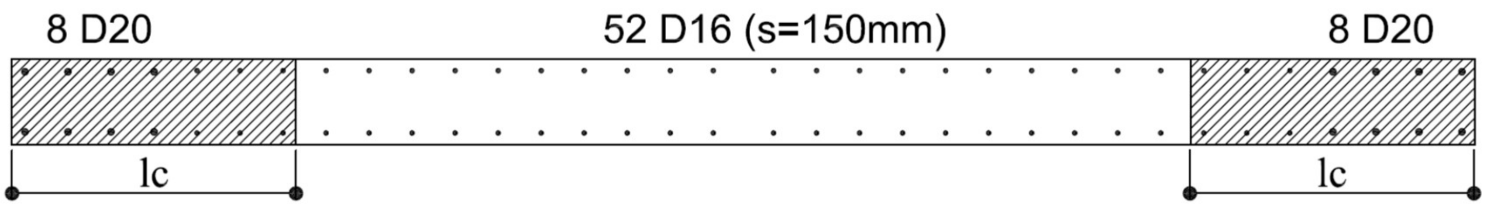
Avoid buckling of the compressed zone:

$b_w \geq max(200mm, h_s/15) = max(200mm, 3840/15=256mm)$: $b_w=300mm$ ✓

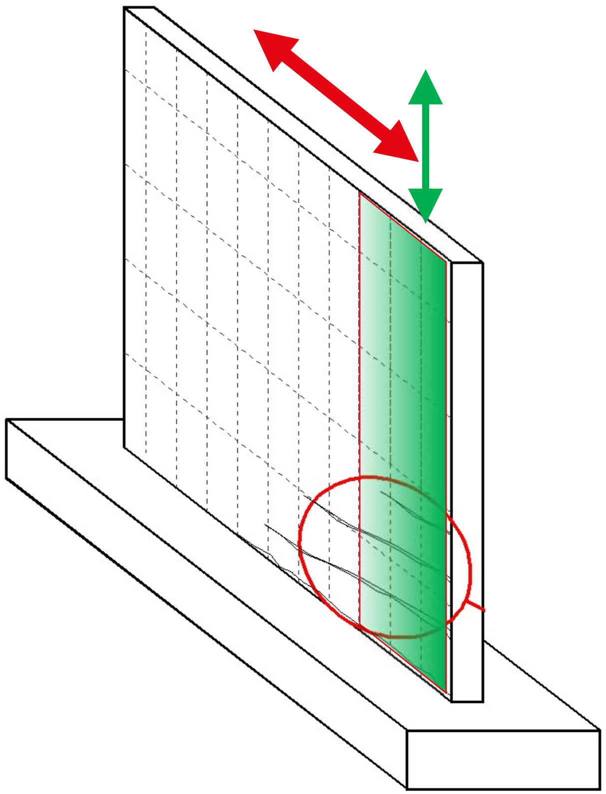
$l_c \geq max(300mm, l_w/10, 0.7x)$ where x = length of the compression zone(x=1.29m)

$l_c \geq max(300mm, 510mm, 920mm) = 920mm$

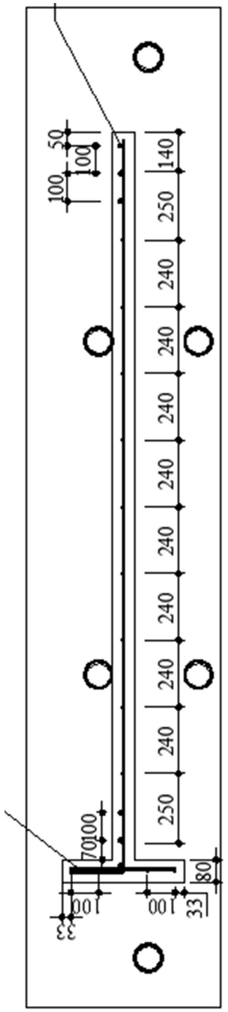
Choice: $l_c=2*45mm+6*150mm=990mm$



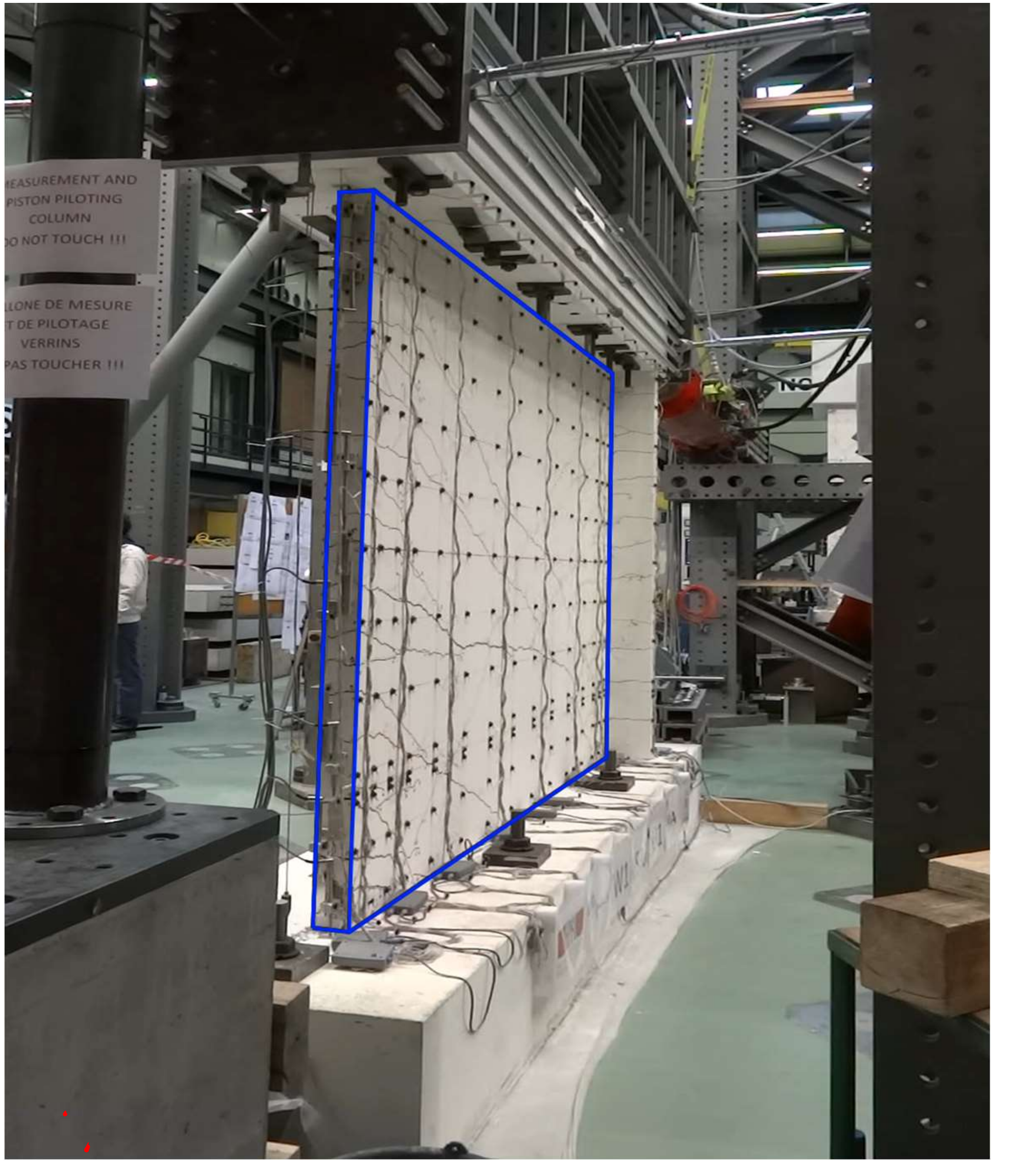
Test on thin RC walls in the lab



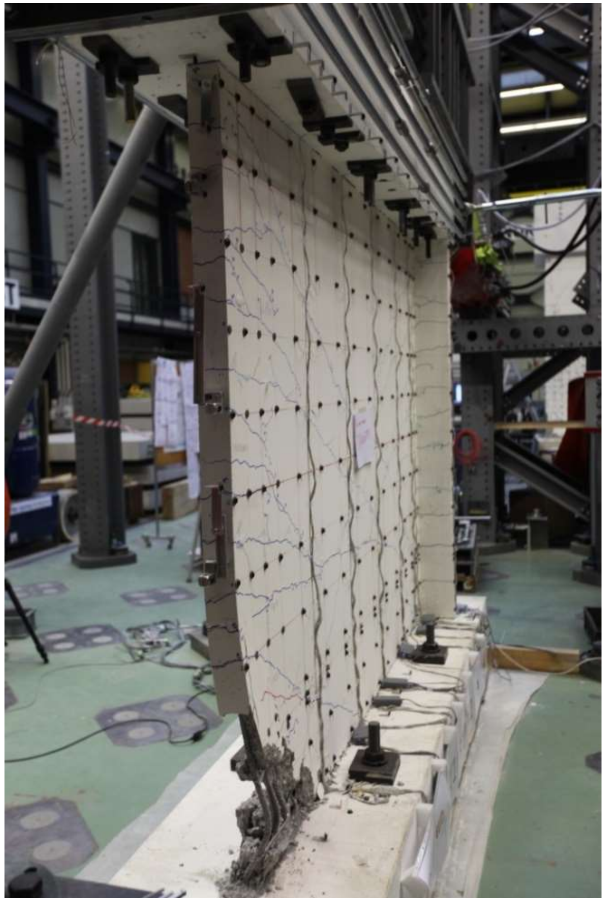
Test on thin RC walls in the lab



Test on thin RC walls in the lab



Test on thin RC walls in the lab



Example: Capacity design

Point 4: Ensure that the curvature capacity of the section is sufficient

Estimate the curvature ductility μ_Φ in the plastic zone:

SIA 262 (2012)

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

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

Example: T_1=1.64s, T_C=0.6s, q=4:

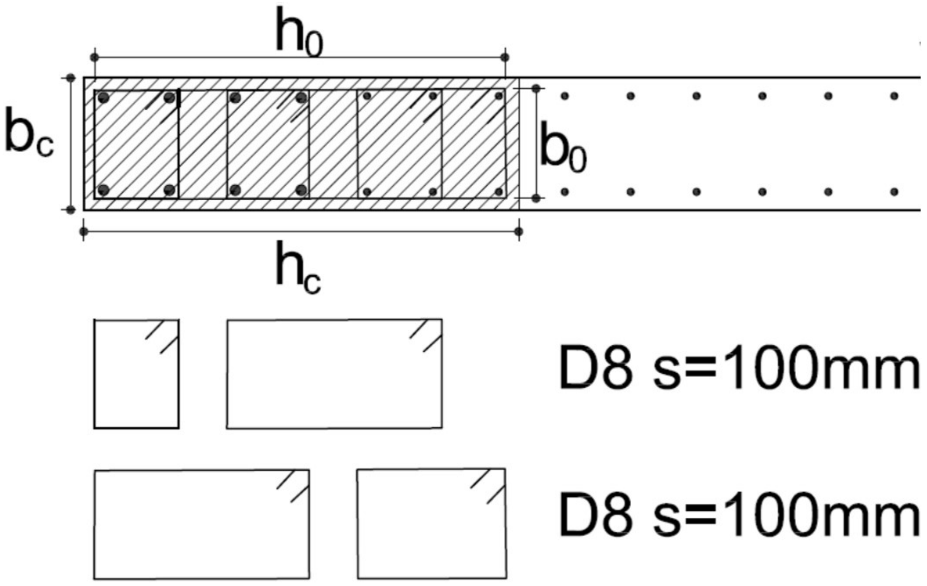
$$\mu_\phi = 7$$

Dr. Francesco Vanin

Example: Capacity design

Point 4: **Ensure that the curvature capacity of the section is sufficient**

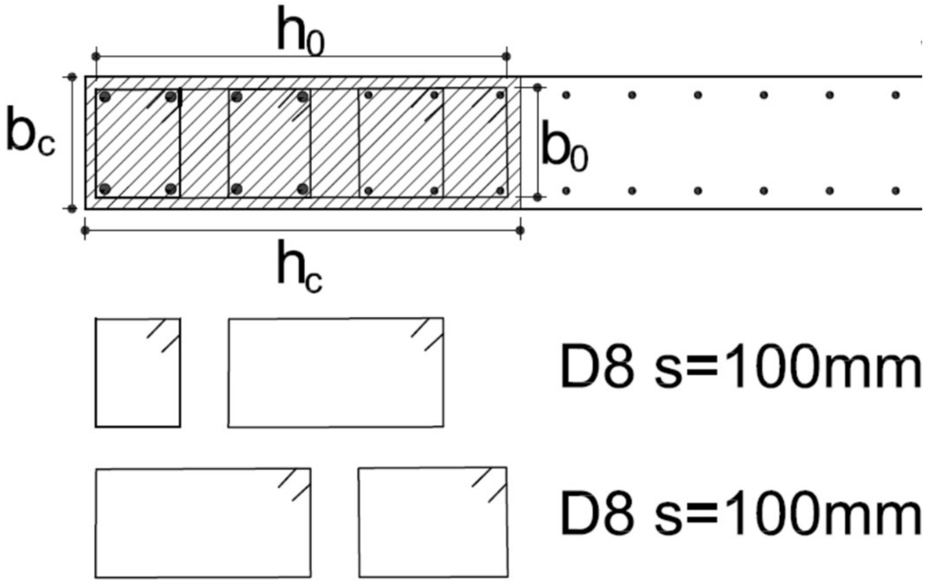
Different hoop layouts are possible. For example:



b_c=300mm, h_c=990mm
b_0=238mm, h_0=928mm

→ Check whether the volumetric confinement ratio is large enough to guarantee the required curvature ductility.

Example: Capacity design



b_c=300mm, h_c=990mm
b_0=238mm, h_0=928mm

Axial load ratio: ν_d=0.09
Mechanical reinforcement content of the web: ω_v=0.15
Curvature ductility of the web: μ_Φ=7
Yield limit of the steel: ε_{syd}=435MPa/200GPa=0.0022

$$\alpha_n = 1 - \frac{\sum b_i^2}{6 b_0 h_0} = 1 - \frac{12 \cdot 150^2 + 2 \cdot 210^2}{6 \cdot 238 \cdot 928} = 0.73$$

$$\alpha_s = (1 - \frac{s}{2b_0})(1 - \frac{s}{2h_0}) = (1 - \frac{100}{2 \cdot 238})(1 - \frac{100}{2 \cdot 928}) = 0.75$$

$$\alpha = \alpha_s \alpha_n = \mathbf{0.55}$$

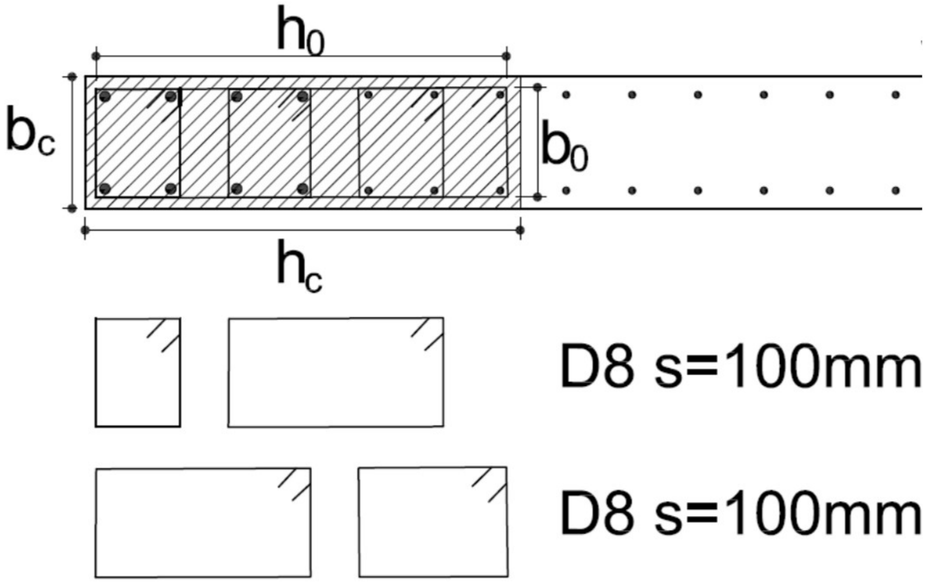
Dr. Francesco Vanin

Example: Capacity design

$$\omega_{wd} \geq \frac{1}{\alpha}\left(30\mu_{\phi}(\nu_d + \varpi_v)\varepsilon_{sy,d}\frac{b_c}{b_0} - 0.035\right) = 0.19$$

Volumetric reinforcement content:

$$\rho_{wd} \geq 0.19\frac{26\,\text{MPa}}{435\,\text{MPa}} = 0.011$$



Confinement reinf.: D8@100mm

$\rho_{wd} = 0.011$ ✓

EPFL

Example: Capacity design

Point 5: Stabilisation of the longitudinal reinforcement in the plastic zone

- Spacing of the hoops:

  $s \leq \min(150mm, 6\Phi_{sl}) = \min(150, 6*16mm = 92mm)$ s=100mm ~✓

- Diameter of the hoops:

  $\Phi_e \geq 0.35\Phi_{sl,max} = 0.35*20mm = 7.0mm$ Φ_e=8mm ✓

- Hoops with 135° hooks ✓
- Every other bar must be stabilised. Distance between stabilised bars must not exceed 200mm. ✓
- Distance between top of foundation and first hoop must not exceed 50mm.

Example: Capacity design

Point 6: Shear design of the plastic zone

- Shear demand accounting for overstrength and dynamic amplification factor:

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

- Amplification factor for overstrength: $\varepsilon = \dfrac{M_{Rd}^+}{M_d}$

- Dynamic amplification factor (n=Number of storeys): $\kappa = 0.9 + \dfrac{n}{10} \leq 1.5$

- Example: n=6 $\kappa = 1.5$

Example: Capacity design

Moment resistance of a RC wall (@ A. Dazio)			
	Ø [mm]	Nombre	A_s [mm^2]
Reinf. of each boundary element	20	8	2513
Web reinforcement	16	52	10455
Total reinforcement			15482
		ρ_w [%] =	0.87
α_e [-] =	0.106	ω_w [-] =	0.20
l_w [m] =	5.1	ρ_e [%] =	1.55
b_w [m] =	0.3	ω_e [-] =	0.36
		ρ_t [%] =	1.01
f_y [MPa] =	600	ω_t [-] =	0.23
f_c [MPa] =	26	ν [-] =	0.09
		α_x [-] =	0.29
N_d [kN] =	3600	m [-] =	0.12
M_{Rd}^+ [kNm] =	25239	x [m] =	1.49

$$\varepsilon = \frac{M_{Rd}^+}{M_d} = \frac{25.2}{20.0} = 1.26$$

Design shear force for plastic zone:

$$V_d^+ = 1.26 \cdot 1.5 \cdot 1370kN = 2590kN$$

Example: Capacity design

Shear design of plastic zone

Example: Horizontal reinforcement:

2D14@200mm ρ_{sw}=0.51%

$\rho_{sw,min}$=max(0.3%; 25%$\rho_{v,tot}$=0.25*1.03%=0.26%)=0.3%

$\rho_{sw} > \rho_{sw,min}$ ✓

a) Horizontal reinforcement (α=45°):

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot f_{sd} \cdot z \cdot \cot\alpha \geq V_d^+ = 2590 kN$$

$$V_{Rd,s} = \frac{2 \cdot 154\, mm^2}{200\, mm} \cdot 435\, MPa \cdot 0.8 \cdot 5.1 m \cdot \cot 45 = 2730\, kN \geq V_d^+$$

b) Diagonal in compression:

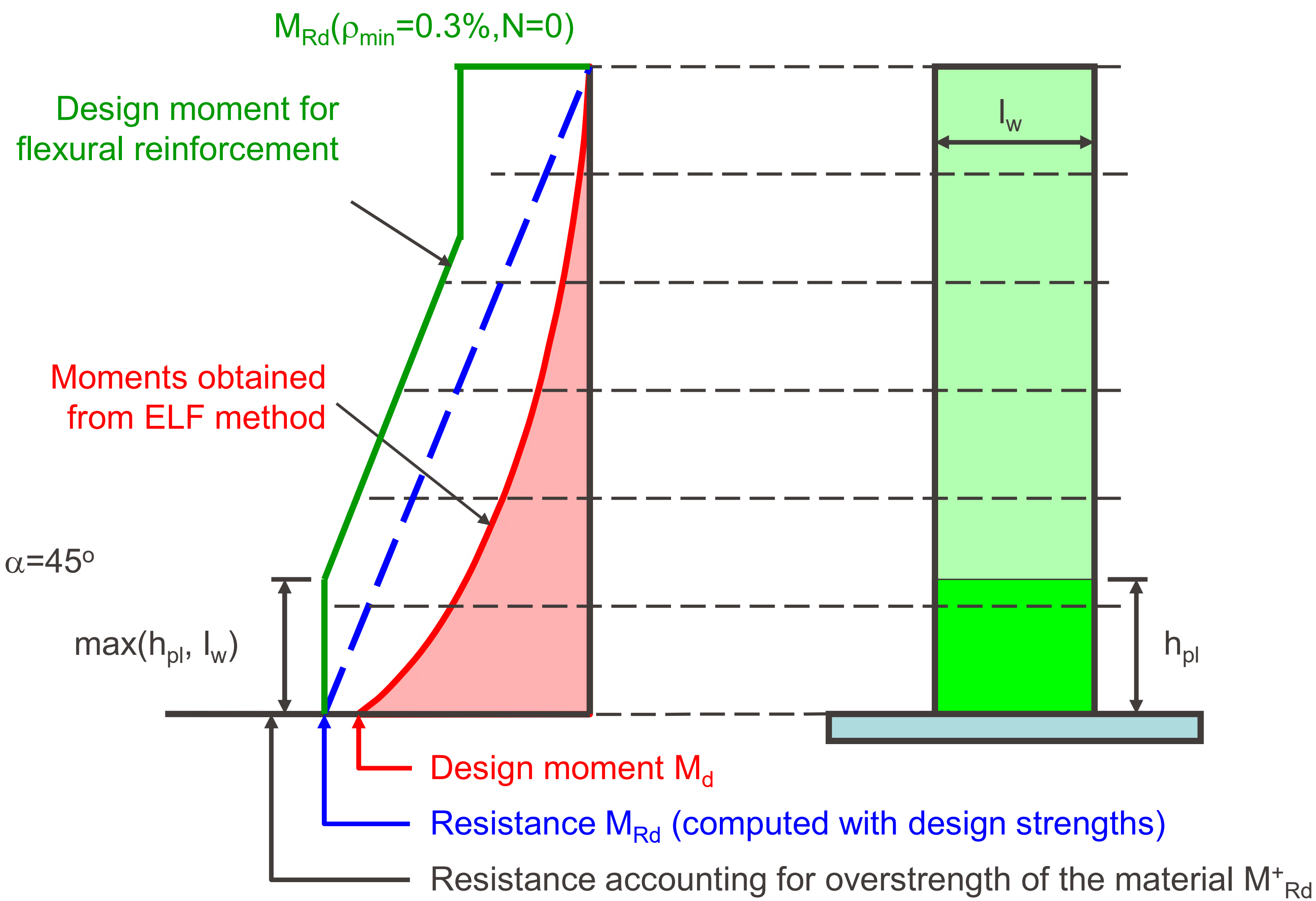
$$V_{Rd,c} = k_c \cdot f_{cd} \cdot b_w \cdot z \cdot \sin\alpha \cdot \cos\alpha \geq V_d^+$$

$$V_{Rd,c} = 0.4 \cdot 26\, MPa \cdot 0.3 m \cdot 0.8 \cdot 5.1 m \cdot \sin 45^o \cos 45^o = 6360\, kN \geq V_d^+$$

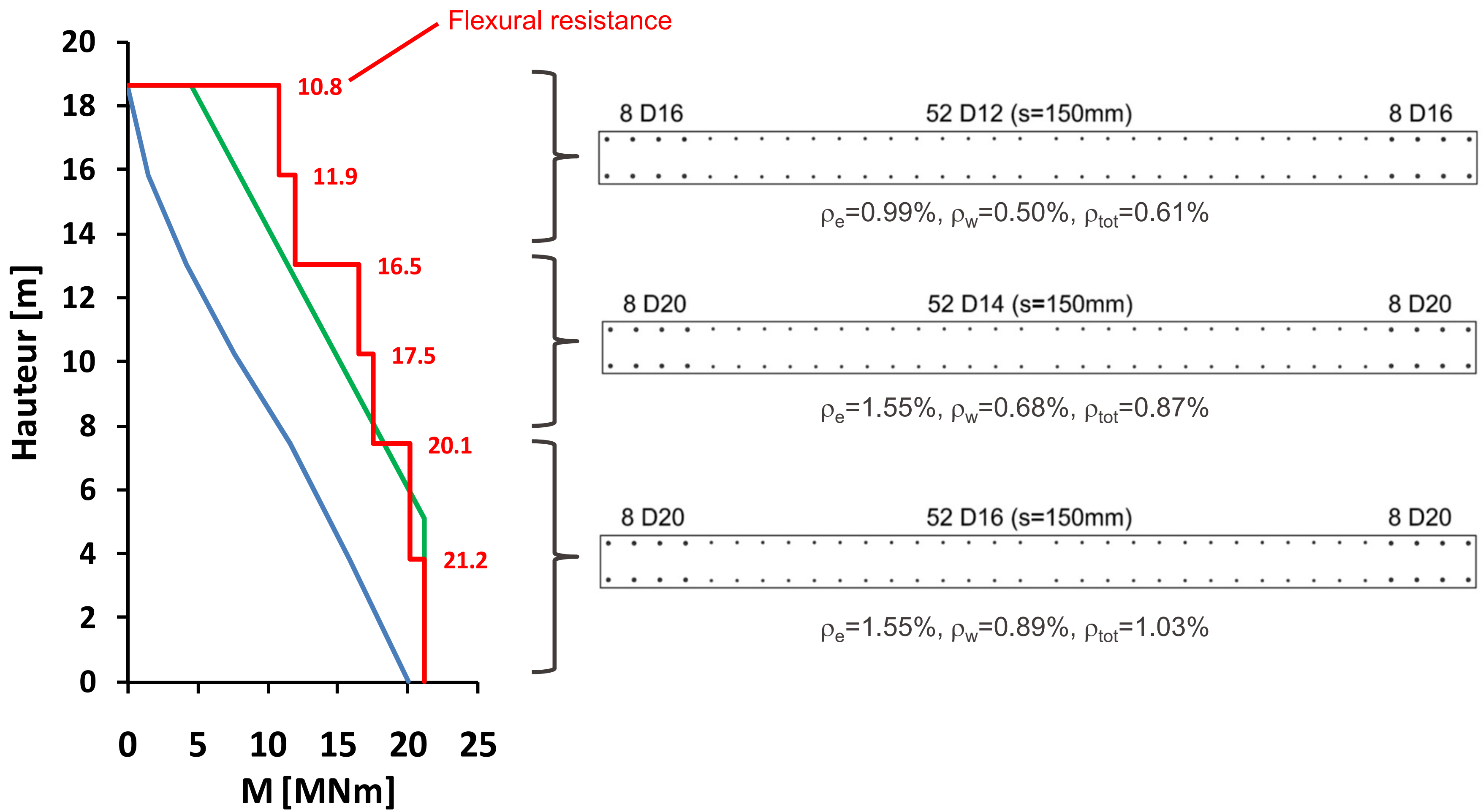
Dr. Francesco Vanin

Capacity design

Point 7: Flexural design of the elastic region

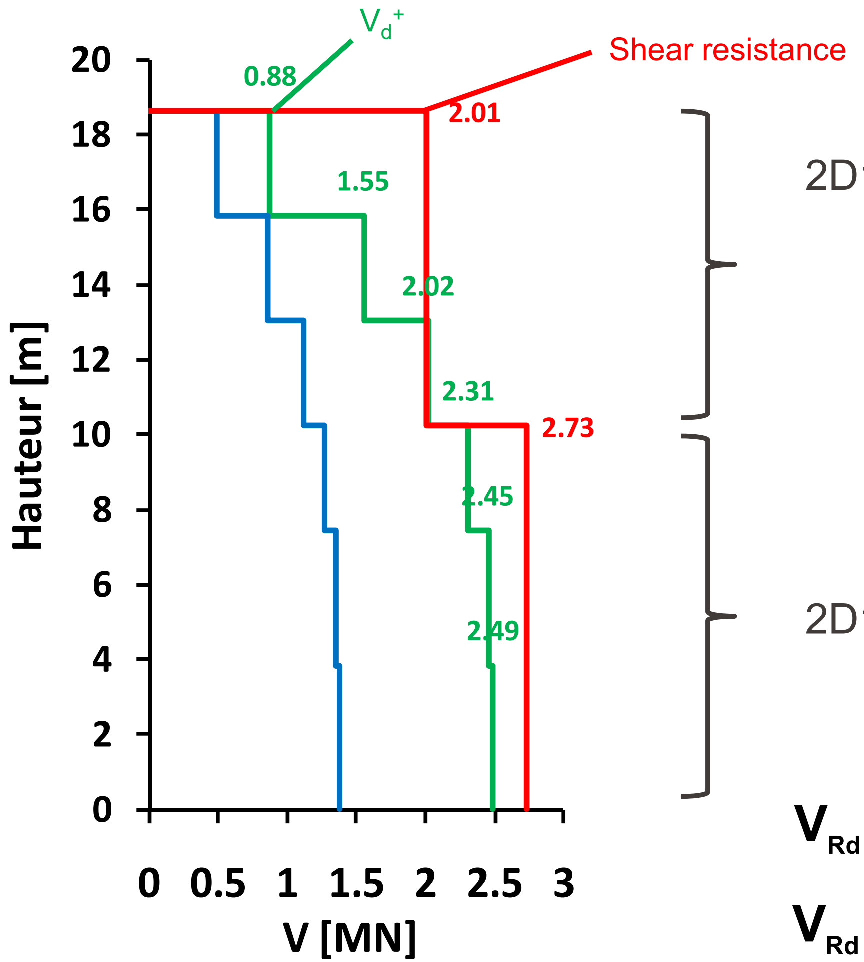


Example: Capacity design



Example: Capacity design

Point 8: **Shear design of the elastic region**



2D12@200mm, ρ_{sv}=0.38%>0.25ρ_{tot}

2D14@200mm, ρ_{sv}=0.51%>0.25ρ_{tot}

$$V_{Rd,s} = \frac{A_{sw}}{s} \cdot f_{sd} \cdot z \cdot \cot\alpha \geq V_d^+$$

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

EPFL

Example: Capacity design

Point 9: Stabilisation of the longitudinal reinforcement in the elastic region

Longitudinal reinforcement in the compression zone:

Not necessary but good practice.

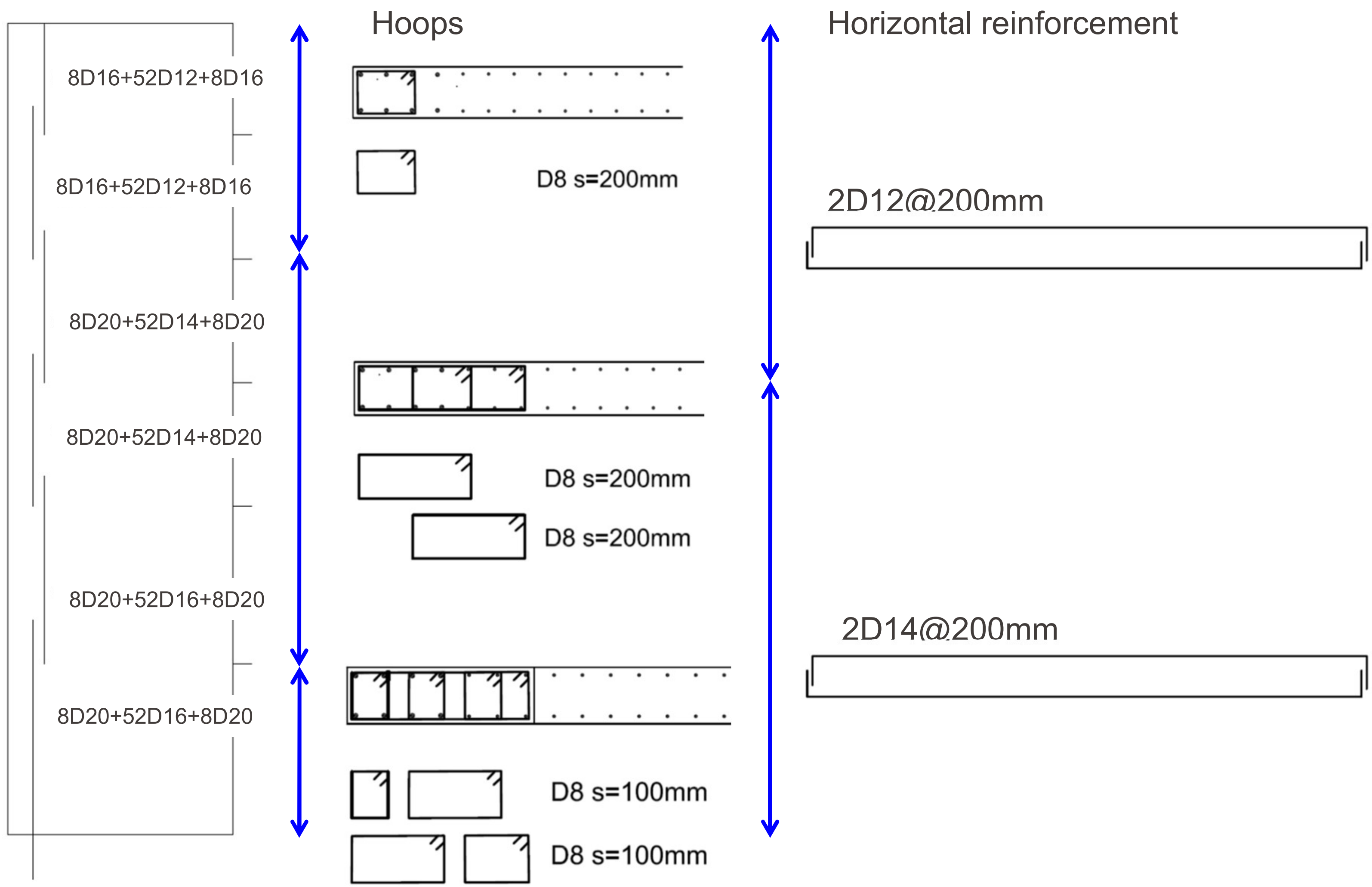
To stabilise the longitudinal reinforcement, limit the hoop spacing:

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

ϕ_{min}	Smallest longitudinal bar diameter in the compression zone
a_{min}	Minimum dimension (=wall width)

Example: s=200mm ≤ min(15*14mm=210mm, 300mm, 300mm) ✓

Example: Capacity design



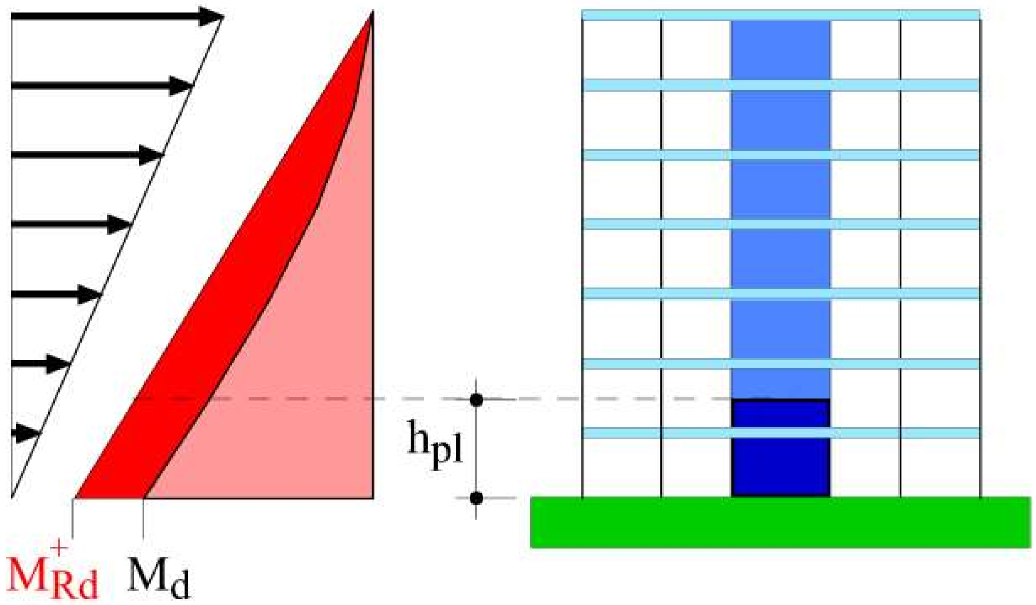
1st hoop @50mm above the foundation

Example: Capacity design

Point 10: Design of the foundation

Consider the overstrength

$$M_{Rd}^{+} = 25.2MNm \qquad V_{d}^{+} = 2.59MN \qquad N_{d} = 3.6MN$$



Capacity designed RC walls under construction

Construction of capacity designed RC walls (Viège)

@ P. Voide

Construction of capacity designed RC walls (Viège)

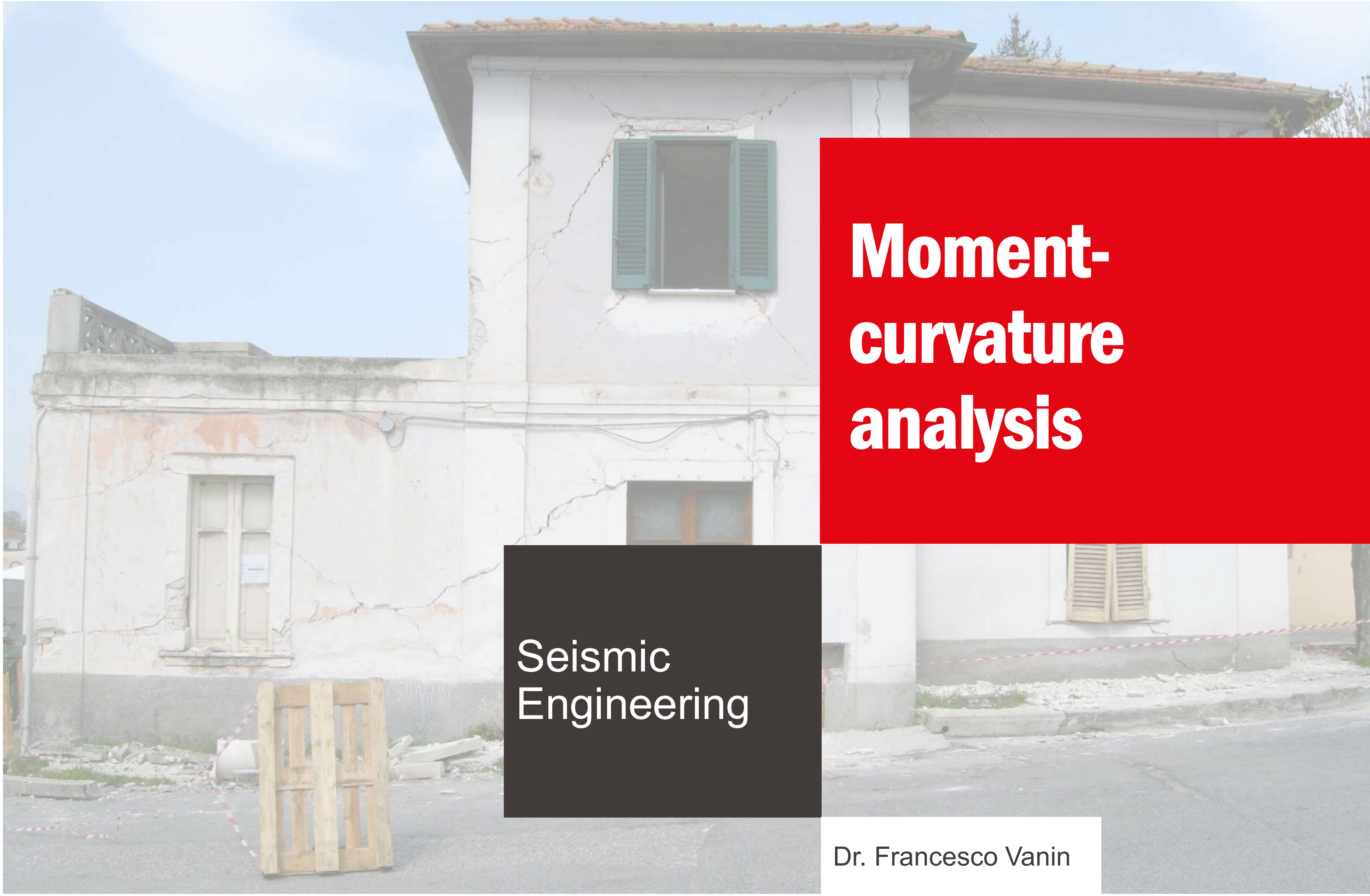
Construction of capacity designed RC walls (Viège)

Construction of capacity designed RC walls (Viège)

EPFL

Construction of capacity designed RC walls (Viège)

EPFL



Moment-curvature analysis

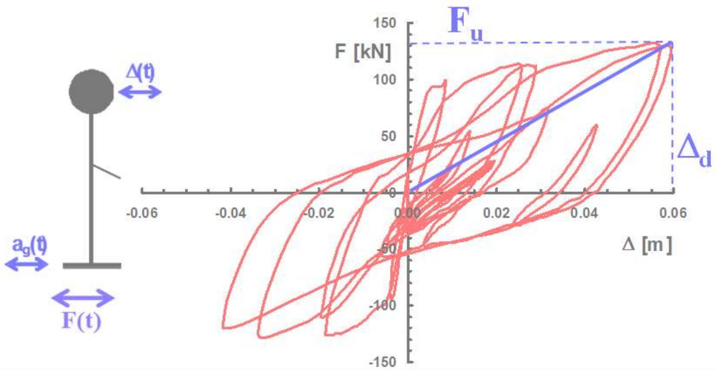
Seismic Engineering

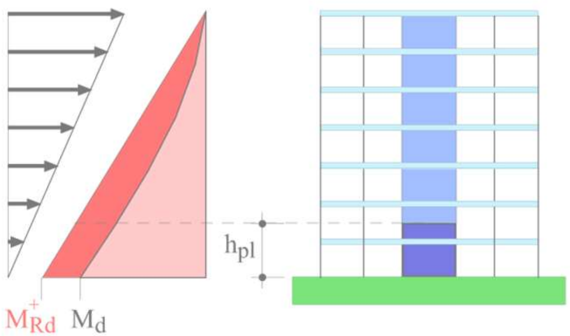
Dr. Francesco Vanin

Course objectives

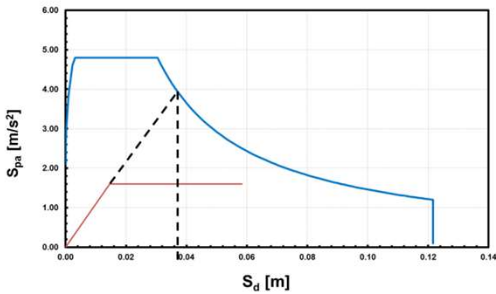
Know typical failure modes of structures during earthquakes.

Know how to estimate the peak forces and displacements of structures subjected to earthquakes.





Know how to design new buildings with reinforced concrete walls.



Know the basic elements of a displacement-based evaluation of existing structures.

Dr. Francesco Vanin

EPFL

Lecture objectives

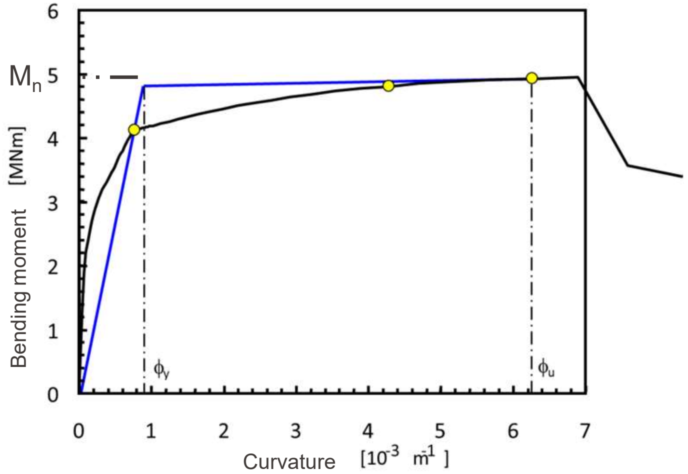
- Learn to compute the moment curvature analysis of a RC section, as a basis for computing the force-displacement capacity of RC walls

Background:

- RC section analysis

Plastic hinge analysis

Response of an RC section

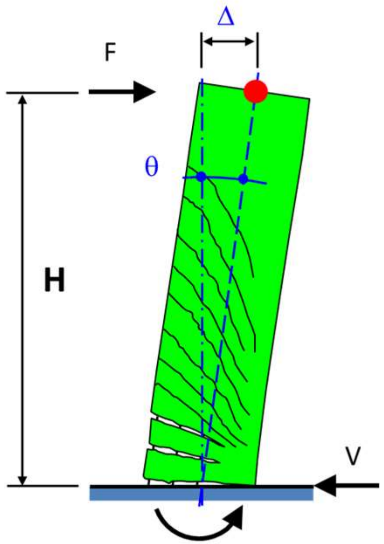


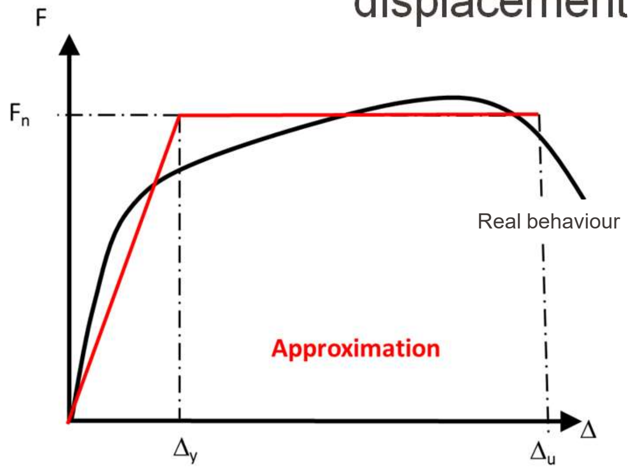
Bilinear approximation of moment-curvature relationship for section that plastifies: M_n, ϕ_y, ϕ_u

Plastic hinge analysis

Bilinear approximation of force-displacement relationship F_n, Δ_y, Δ_u

Response of an RC member



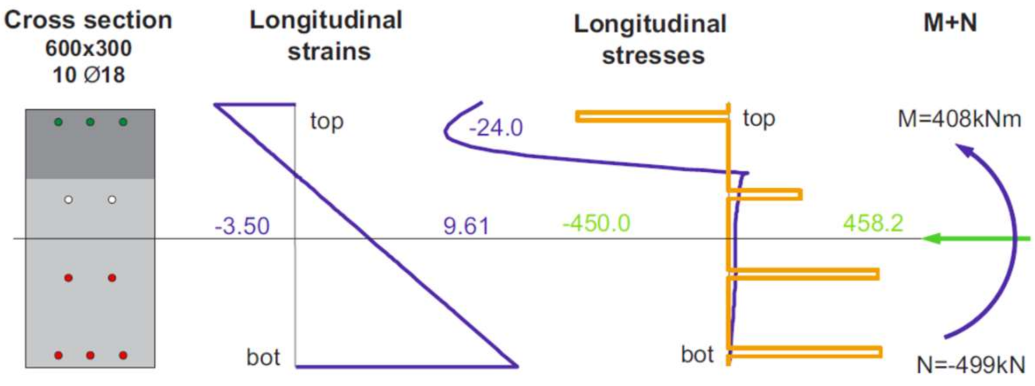


Objective: Estimate with simple means the inelastic displacement capacity

Moment-curvature analysis

Moment-curvature analysis

= Computation of moment for increasing curvature and constant axial force



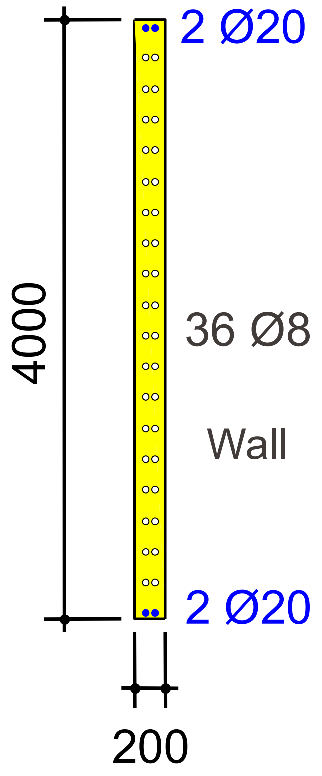
Required input:

- Geometry of RC section
- Stress-strain relationships of confined and unconfined concrete and of longitudinal reinforcement bars

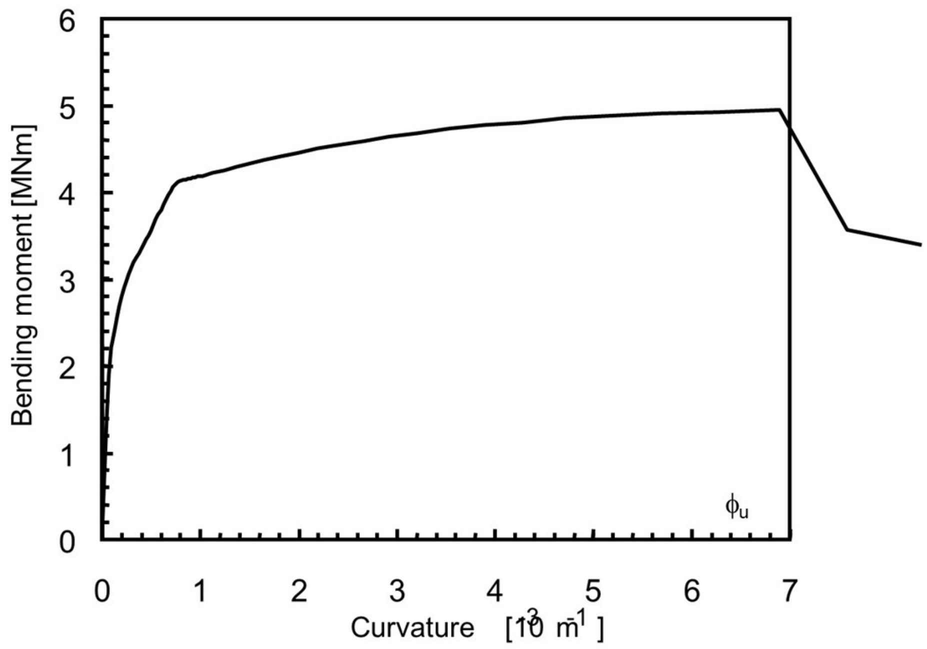
Assumptions:

- Linear strain profile («plane sections remaining plane», Bernoulli)
- Perfect bond between reinforcement and concrete → Strain only dependent on the distance to neutral axis

Moment-curvature relationship



N = -1099 kN



@ A. Dazio

Moment-curvature analysis

Procedure: Moment-curvature analysis for a constant axial force N

- Divide section into layers
- Determine for each layer the area of unconfined concrete, confined concrete and reinforcing steel
- Define stress-strain relationship for unconfined concrete, confined concrete and reinforcing steel

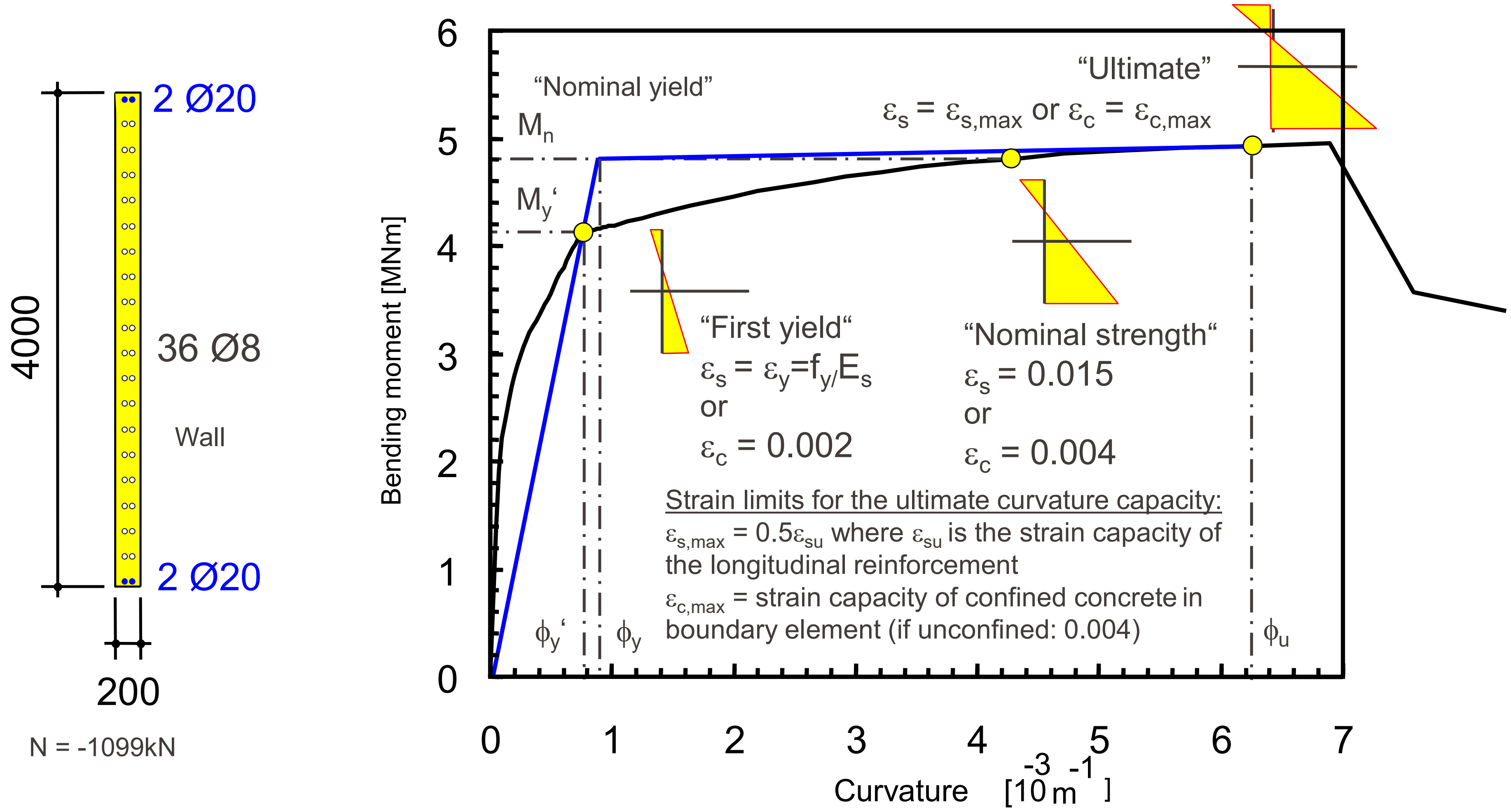
- Choose a strain of the extreme compression fibre ε_c
- Assume a neutral axis depth c
- Compute strain at the centreline of each layer
- Calculate for each layer the concrete and reinforcement stress (from stress-strain relationship)
- Calculate for each layer the concrete and reinforcement forces
- Check whether the sum of all concrete and reinforcement forces gives the axial force N
- If not, modify c and iterate until agreement is satisfactory.
- Compute the moment M and the curvature ϕ

- Increase the strain of the extreme compression fibre ε_c to compute further points of the moment-curvature relationship

Moment-curvature analysis

Moment-curvature analysis

Moment-curvature analysis – bilinear approximation



References

Key references:

- Dazio, A. (2005) “Capacité portante des constructions en béton”, SIA Documentation D 0211 “Vérification de la sécurité parasismique des bâtiments existants”. (sur le page web du cours)
- Dazio, A. (2009) , Cours notes for post-graduate course at the University of Stellenbosch.
- Hannewald, P., Bimschas, M., Dazio, A. (2013) “Quasi-static cyclic tests on RC bridge piers with detailing deficiencies,” IBK Report, ETH Zürich, Switzerland.
- Lestuzzi, P. (2011), Cours de génie parasismique, EPFL.

Further references:

- Beyer, K., Dazio, A. and Priestley, M.J.N. (2008) “Quasi-static cyclic tests of two U-shaped reinforced concrete walls,” Journal of Earthquake Engineering 12(7): 1023-1053.
- Bentz E. (2001) “Response-2000 User Manual”. Version 1.1. Department of Civil Engineering, University of Toronto. Canada.
- Dazio, A., Wenk, T. and Bachmann, H. (1999) “Versuche an Stahlbetontragwänden unter zyklisch-statischer Einwirkung”, IBK-Report No 239, Birkhäuser, Zürich, Switzerland.
- Paulay T., Priestley M.J.N. (1992) “Seismic Design of Reinforced Concrete and Masonry Buildings”. John Wiley & Sons, New York, United States.
- Priestley, M.J.N., Seible, F. and Calvi, G.M. (1996) “Seismic design and retrofit of bridges”, John Wiley and Sons, New York, United States.
- Restrepo-Posada J.I. (1993) “Seismic Behaviour of Connections Between Precast Concrete Elements”. Report 93-3. Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.