ULS Verification of Core Walls in Accordance with EN1998-1:2004

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Content

Introduction

- Basic code requirements
- Verification algorithm

Numerical Example

- Verification of ULS limit states for complexly shaped Core Wall

Optimization?

- How to improve solutions and what to avoid in practice?

Conclusions

- Summary of previous chapters

1. Introduction

- Focal point will be on core walls as they are the most often used element for lateral stability in mid-rise and high-rise buildings
- Special emphasis is on the verifications of ductility requirements in walls of complex geometry

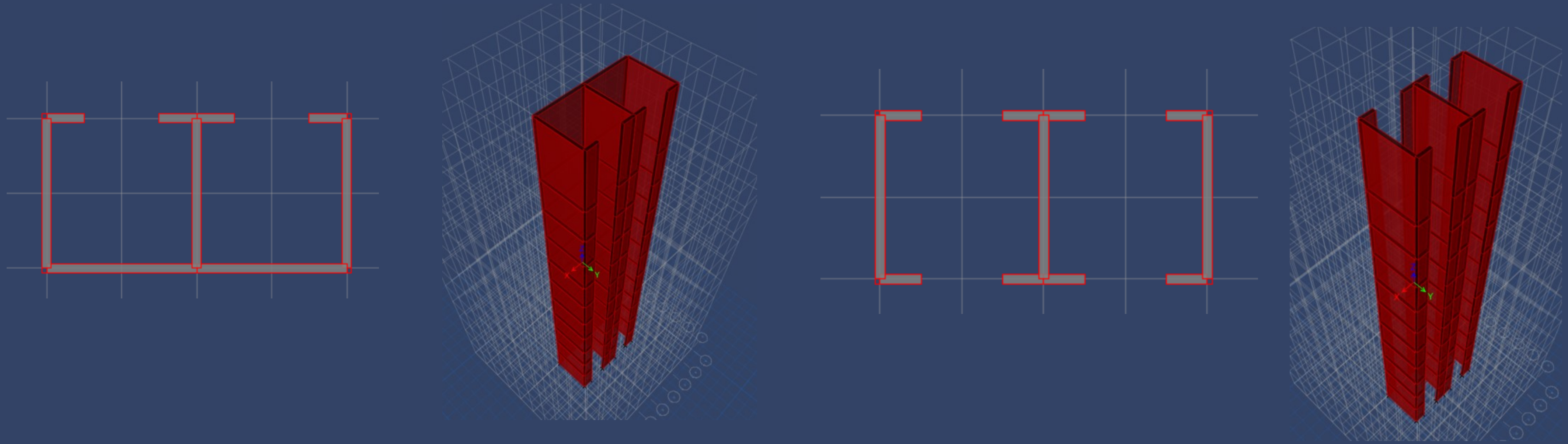

Figure 1: Common shapes of Core Walls

- Important clauses from Code [1]

[1] – EN1998-1:2004

1.1 Basic code requirements [1]

5.2.1 (1) [1]

5.4.3.4.1 (4) [1

5.4.3.4.2 (5) [1

Summary

!

Ductile wall:

Ductile wall is an element fixed at its base so that the relative rotation of this base with respect to the rest of the structural system is prevented, and that is designed and detailed to dissipate energy ***in a flexural plastic hinge zone free of openings or large perforations, just above its base.***

[1] – EN1998-1:2004

1.1 Basic code requirements [1]

5.2.1 (1) [1]

5.4.3.4.1 (4) [1]

5.4.3.4.2 (5) [1

Summary

!

Walls of complex geometry:

Composite wall sections consisting of connected or intersecting rectangular segments (L-, T-, U-, I or similar sections) ***should be taken as integral units***, consisting of a web or webs parallel or approximately parallel to the direction of the acting seismic shear force and a flange or flanges normal or approximately normal to it

**Effective width of flange should be accounted for*

[1] – EN1998-1:2004

1.1 Basic code requirements [1]

5.2.1 (1) [1]

5.4.3.4.1 (4) [1

5.4.3.4.2 (5) [1]

Summary

!

Length of confinement zone:

For walls with barbells or flanges, or with a section consisting of several rectangular parts (L-, T-, U-, I-shaped sections, etc.) the mechanical volumetric ratio of the confining reinforcement in the boundary elements may be determined as follows:

$$x_u = (v_d + \omega_v) \cdot \frac{l_w \cdot b_c}{b_0}$$

**Applicable only for rectangular compressive zone*

[1] – EN1998-1:2004

1.1 Basic code requirements [1]

5.2.1 (1) [1]

5.4.3.4.1 (4) [1

5.4.3.4.2 (5) [1

Summary

How to assess core walls?

- Avoid the problem by designing only rectangular shear walls
- Keep increasing the width of the compressed zone so it remains rectangular
- ***Perform more in-depth analysis to determine the actual curvature ductility of the composite core wall section***

[1] – EN1998-1:2004

1.1 Basic code requirements [1]

Ductility requiermernts

Goal is to verify that section has sufficient curvature ductility:

$$\mu_{\phi.cap} \geq \mu_{\phi.req}$$

$$\mu_{\phi.req} = \begin{cases} 2 \cdot q_0 - 1, & T_1 \geq T_C \\ 1 + 2 \cdot (q_0 - 1) \cdot \dfrac{T_C}{T_1}, & T_1 < T_C \end{cases}$$

$$\mu_{\phi.cap} = \frac{\mu_u}{\mu_y}$$

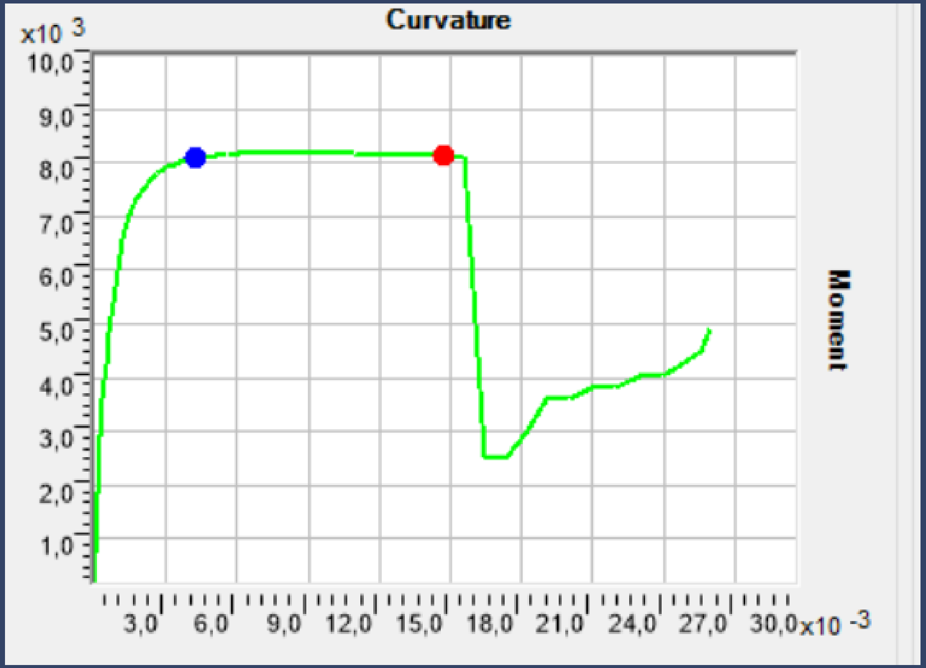

Figure 2: Moment-Curvature Diagram

[1] EN1998-1:2004

1.2. Verification algorithm [2]

1.2.1 Calculate curvature on the onset of yielding μ_y

Section is considered to start yielding when either of criteria is met:

Expected behaviour in shear walls

Reinforcement reaches its yield strain ε_{sy}

Possible behaviour in members with high axial compression – not expected in shear walls

Concrete reaches characteristic strain ε_c^*

[2] – Seismic Design, Assessment and Retrofitting of Concrete Buildings – M. Fardis

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Expected behaviour in shear walls

Reinforcement reaches its yield strain ε_{sy}

Possible behaviour in members with high axial compression – not expected in shear walls

Concrete reaches characteristic strain $\varepsilon_c^* = 1.8 \cdot \frac{f_c}{E_c}$

[2] – Seismic Design, Assessment and Retrofitting of Concrete Buildings – M. Fardis

1.2. Verification algorithm [2]

1.2.2 Calculate ultimate curvature μ_u

Section can reach its ultimate curvauture in one of four modes:

Failure before spalling of concrete cover
Reinforcement reaches its ultimate strain ε_{su}

Failure before spalling of concrete cover
Unconfined concrete reaches its ultimate strain ε_{cu}

Failure after spalling of concrete cover
Reinforcement reaches its ultimate strain ε_{su}

Failure after spalling of concrete cover
Confined concrete reaches its ultimate strain $\varepsilon_{cu.c}$

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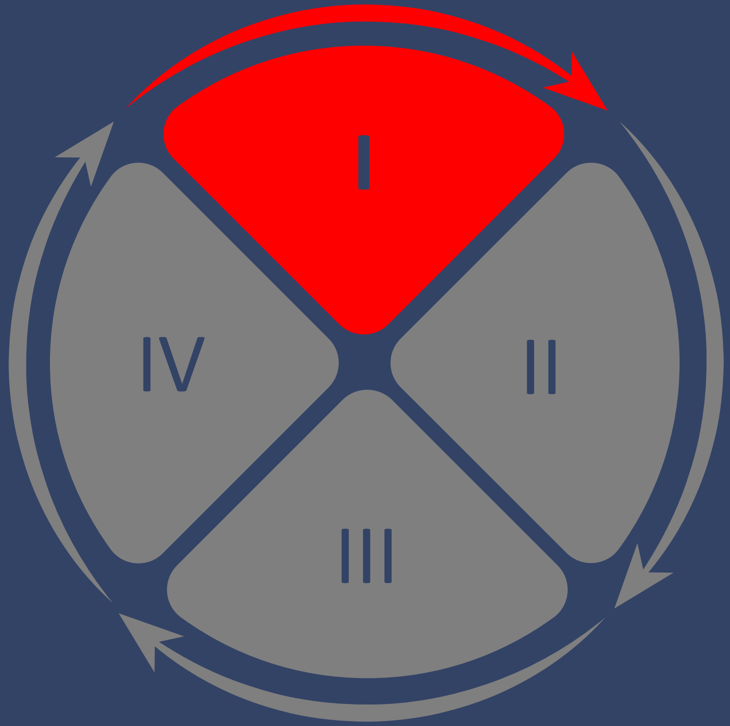

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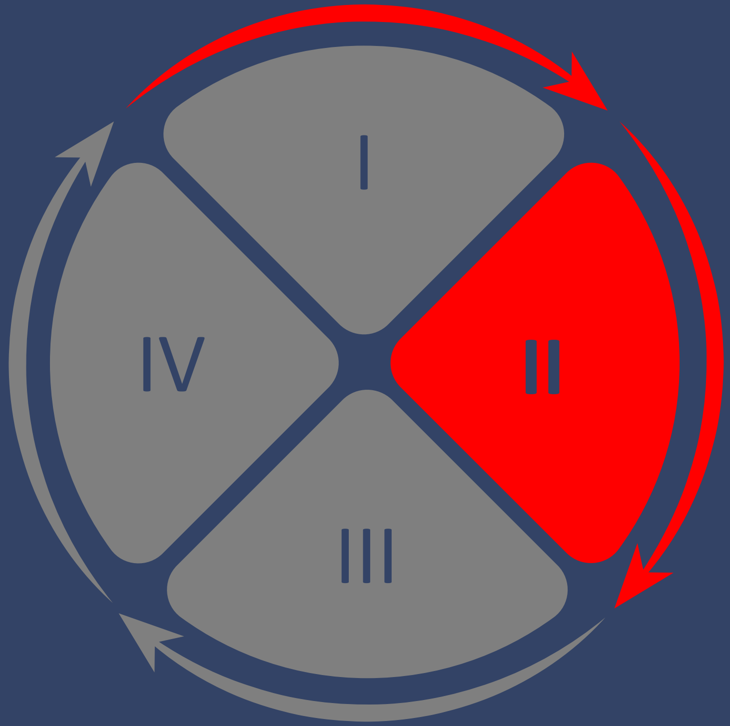

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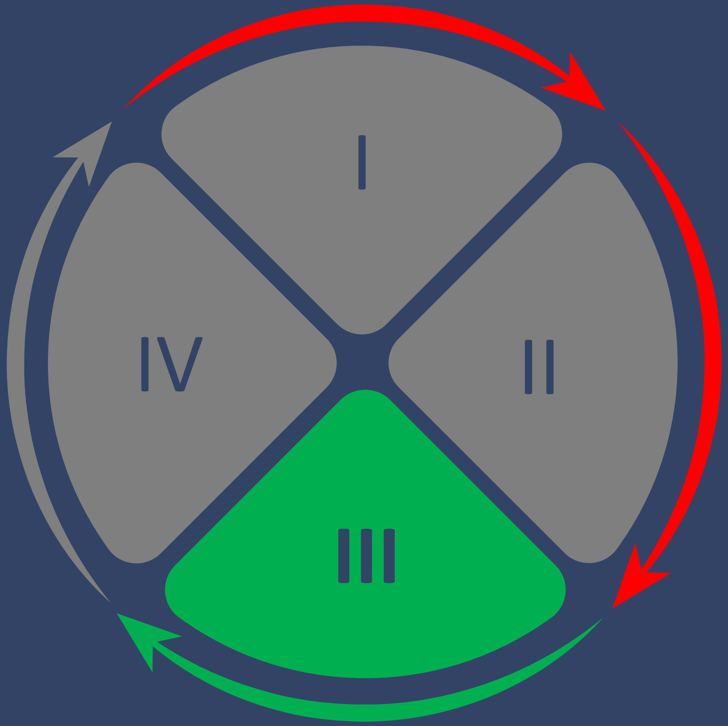

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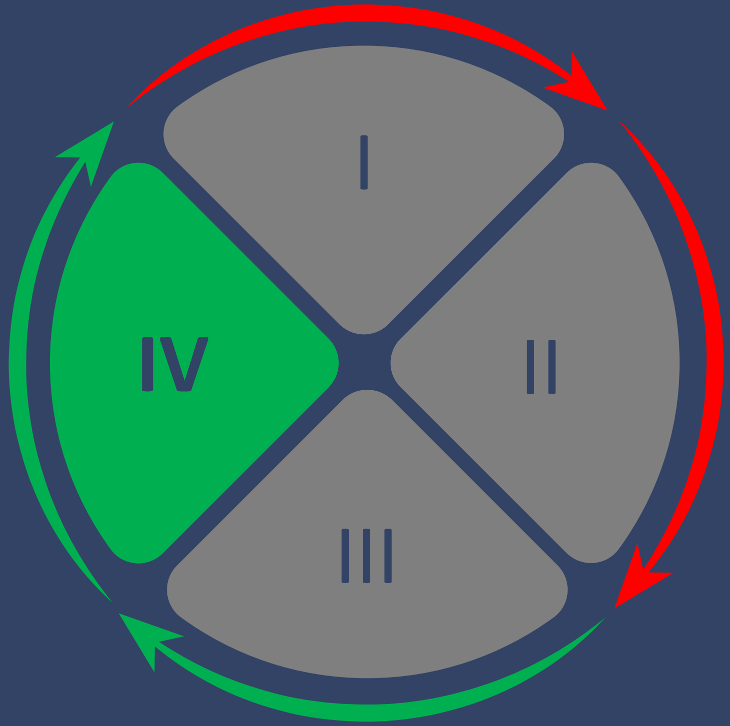

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2. Numerical example

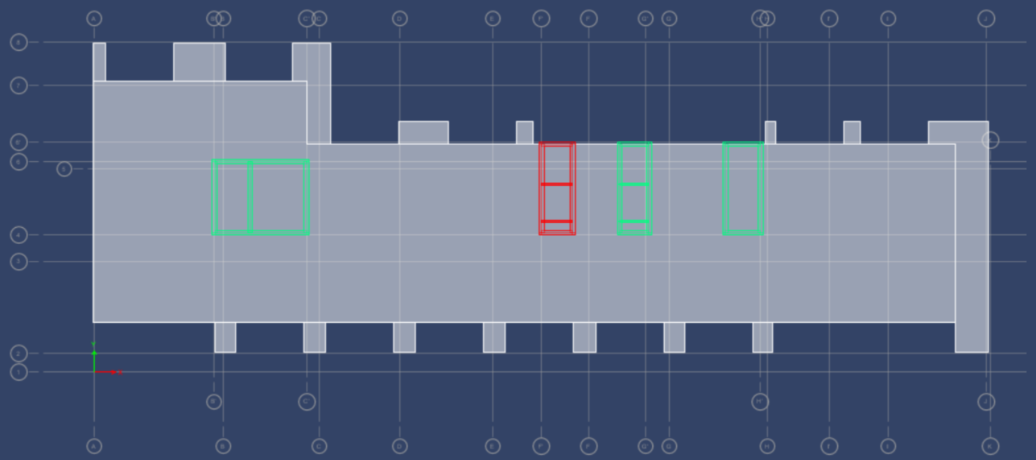


Figure 3: Analyzed core wall in plan view

Height	84m
Stories	23
q_0	2
Concrete	C50/60
Reinforcement	B500B
T_f	3s
T_c	0,5s

Ductility class	DCM
a_g/g	0,10

Table 1: Basic structure properties

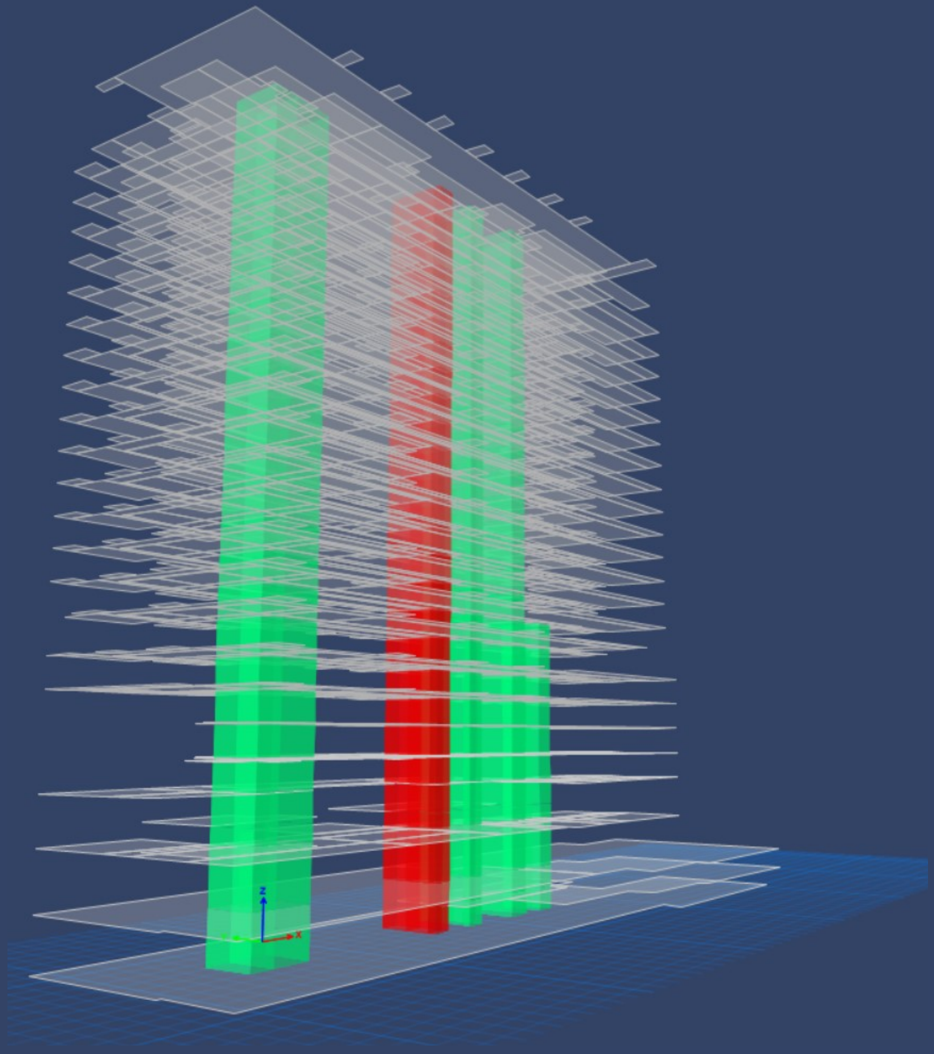


Figure 4: Analyzed core wall in isometric view

2. Numerical example

2.1. Core wall as an assemblage of independent shear walls?

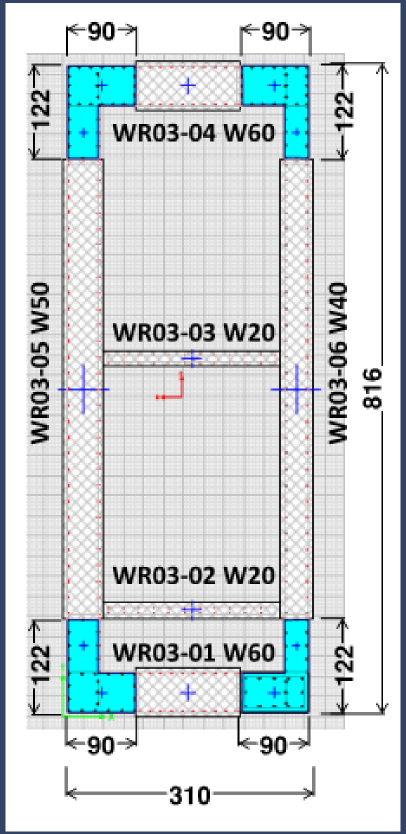


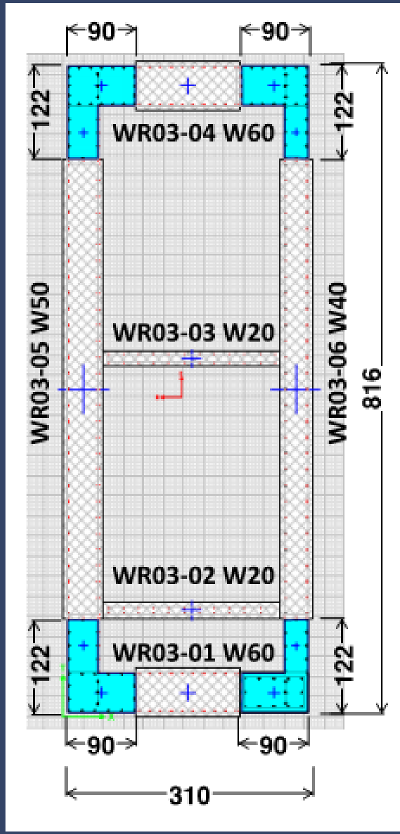
Figure 5: Confined zones and dimensions of core wall

2. Numerical example

2.1. Core wall as an assemblage of independent shear walls?

Comment	Wall	Combo	l_w [m]	b_w [m]	N_{ed} [kN]	v	Web RFT		Confined RFT		M_{ed} [kNm]	M_{Rd} [kNm]	M_{Ed}/M_{Rd} [%]	$l_{c.geo}$ [m]	$l_{c.calc}$ [m]	$l_{c.adp}$ [m]	Comment
Governing	WR03-01	MAX	3,10	0,60			12	150	16	200			**29,23**				
Seismic Combo	WR03-01	Nmax S	3,10	0,60	18000	0,34	12	150	16	200	1500	22687	6,61	0,90	**0,90**	**0,90**	Minimal geometrical length
	WR03-01	Nmin S	3,10	0,60	100	0,00	12	150	16	200	1500	5132	29,23	0,90	**0,90**	**0,90**	
	WR03-01	Tension Force S	3,10	0,60	0	0,00	12	150	16	200	0	0	0,00	-	-	-	
Governing	WR03-04	MAX	3,10	0,60			12	150	16	150			**83,59**				
Seismic Combo	WR03-04	Nmax S	3,10	0,60	15500	0,29	12	150	16	150	1600	22193	7,21	0,90	**0,90**	**0,90**	Minimal geometrical length
	WR03-04	Nmin S	3,10	0,60	14000	0,27	12	150	16	150	1600	21139	7,57	0,90	**0,90**	**0,90**	
	WR03-04	Tension Force S	3,10	0,60	-3200	-0,06	12	150	16	150	1600	1914	83,59	-	-	-	
Governing	WR03-05	MAX	8,16	0,50			12	200	16	200			**54,43**				
Seismic Combo	WR03-05	Nmax S	8,16	0,50	24200	0,21	12	200	16	200	33000	97361	33,89	1,22	**1,22**	**1,22**	Minimal geometrical length
	WR03-05	Nmin S	8,16	0,50	11000	0,10	12	200	16	200	33000	60631	54,43	1,22	**1,22**	**1,22**	
	WR03-05	Tension Force S	8,16	0,50	0	0,00	12	200	16	200	0	0	0,00	-	-	-	
Governing	WR03-06	MAX	8,16	0,40			12	200	16	200			**49,30**				
Seismic Combo	WR03-06	Nmax S	8,16	0,40	17000	0,18	12	200	16	200	22000	75270	29,23	1,22	**1,22**	**1,22**	Minimal geometrical length
	WR03-06	Nmin S	8,16	0,40	6400	0,07	12	200	16	200	22000	44626	49,30	1,22	**1,22**	**1,22**	
	WR03-06	Tension Force S	8,16	0,40	0	0,00	12	200	16	200	0	0	0,00	-	-	-	

Table 2: Verification of constituent walls as independent shear walls



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Governing	WR03-01	MAX	3,10	0,60			Minimal reinforcement				**29,23**				Minimal length of boundary zone
Seismic Combo	WR03-01	Nmax S	3,10	0,60	18000	**0,34**			1500	22687	6,61	0,90	**0,90**	**0,90**	
	WR03-01	Nmin S	3,10	0,60	100	**0,00**			1500	5132	29,23	0,90	**0,90**	**0,90**	
	WR03-01	Tension Force S	3,10	0,60	0	**0,00**			0	0	0,00	-	-	-	
Governing	WR03-04	MAX	3,10	0,60			*Almost minimal reinforcement*				**83,59**				Minimal length of boundary zone
Seismic Combo	WR03-04	Nmax S	3,10	0,60	15500	**0,29**			1600	22193	7,21	0,90	**0,90**	**0,90**	
	WR03-04	Nmin S	3,10	0,60	14000	**0,27**			1600	21139	7,57	0,90	**0,90**	**0,90**	
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Table 2: Verification of constituent walls as independent shear walls

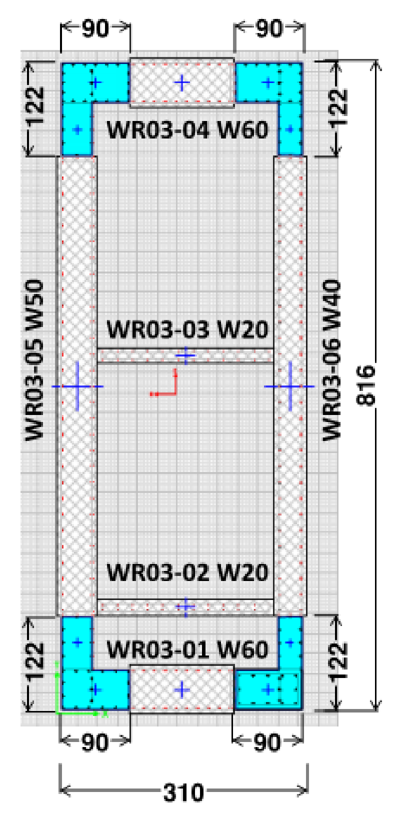

Figure 5: Confined zones and dimensions of core wall

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2.1. Core wall as an assemblage of independent shear walls?

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Governing	WR03-01	MAX	3,10	0,60			12	150	16	200			**29,23**				Minimal length of boundary zone
Seismic Combo	WR03-01	Nmax S	3,10	0,60	18000	**0,34**	Minimal reinforcement				1500	22687	6,61	0,90	**0,90**	**0,90**	
	WR03-01	Nmin S	3,10	0,60	100	**0,00**					1500	5132	29,23	0,90	**0,90**	**0,90**	
	WR03-01	Tension Force S	3,10	0,60	0	**0,00**	12	150	16	200	0	0	0,00	-	-	-	
Governing	WR03-04	MAX	3,10	0,60			12	150	16	150			**83,59**				Minimal length of boundary zone
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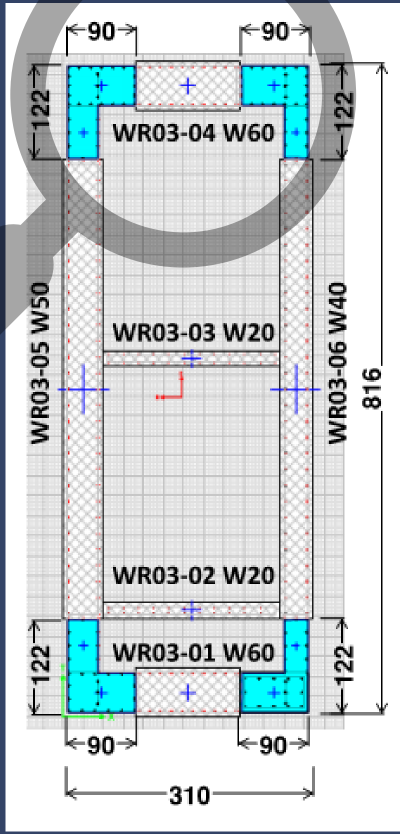


Figure 5: Confined zones and dimensions of core wall

2. Numerical example

2.2. Core wall as an integral element

Global analysis Tower			
$M_{2.max}$	$M_{2.min}$	$M_{3.max}$	$M_{3.min}$
[kNm]	[kNm]	[kNm]	[kNm]
16500	-31000	138000	-99500
Axial force [kN]			
$N_{max.c}$	**-55000**	**$N_{min.c}$**	**-40000**

Table 3: Results of global analysis

Local analysis SAP2000			
$M_{1.Ed}$	$M_{2.Ed}$	$M_{3.Ed}$	$M_{4.Ed}$
[kNm]	[kNm]	[kNm]	[kNm]
139000	**101000**	**105000**	**142000**
φ_1	φ_2	φ_3	φ_4
[°]	[°]	[°]	[°]
6,82	**170,58**	**197,30**	**347,34**

Table 4: Acting bending moments on concrete core

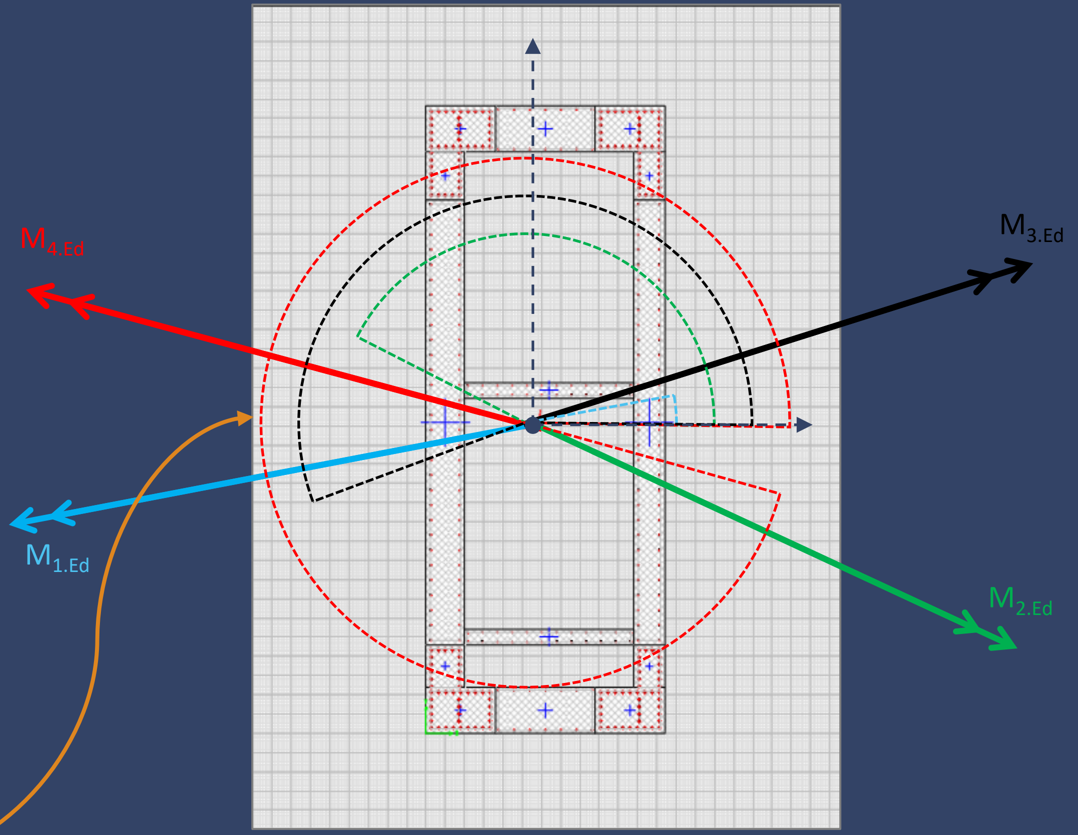


Figure 6: Resultant biaxial bending moments

2. Numerical example

2.2. Core wall as an integral element

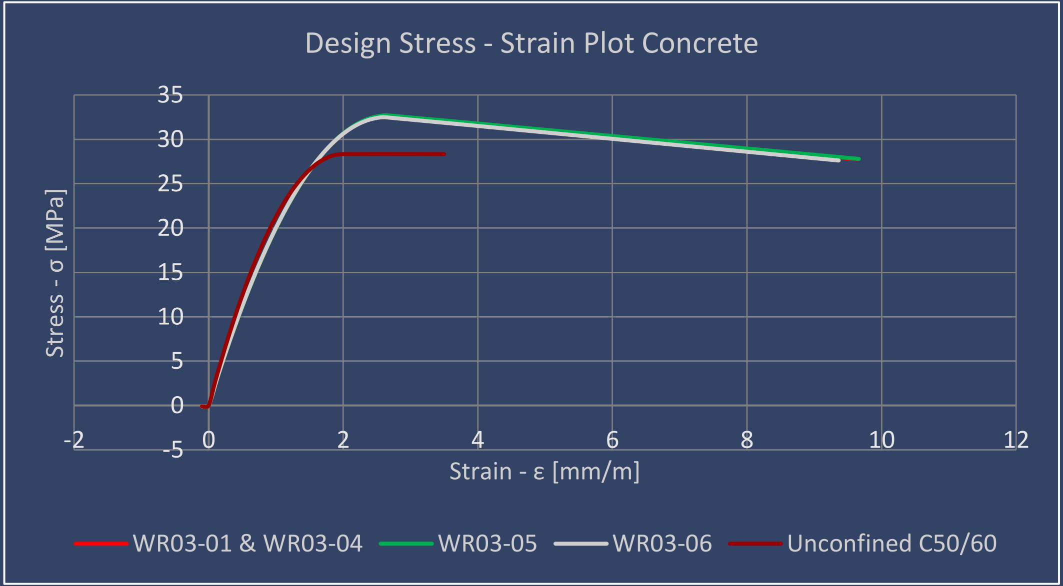


Figure 7: Concrete properties used in analysis

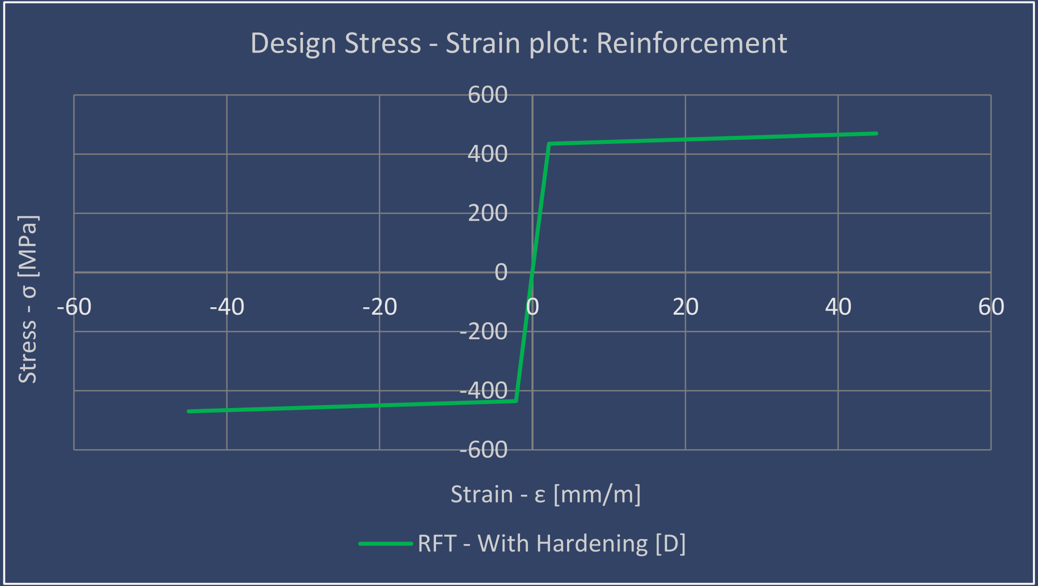


Figure 8: Reinforcement properties used in analysis

2. Numerical example

2.2.1. Core wall as an integral element – Curvature at the onset of yielding

- CSi SAP2000 v21.2.0 is used to monitor stresses and strains in section

Curvature ductility

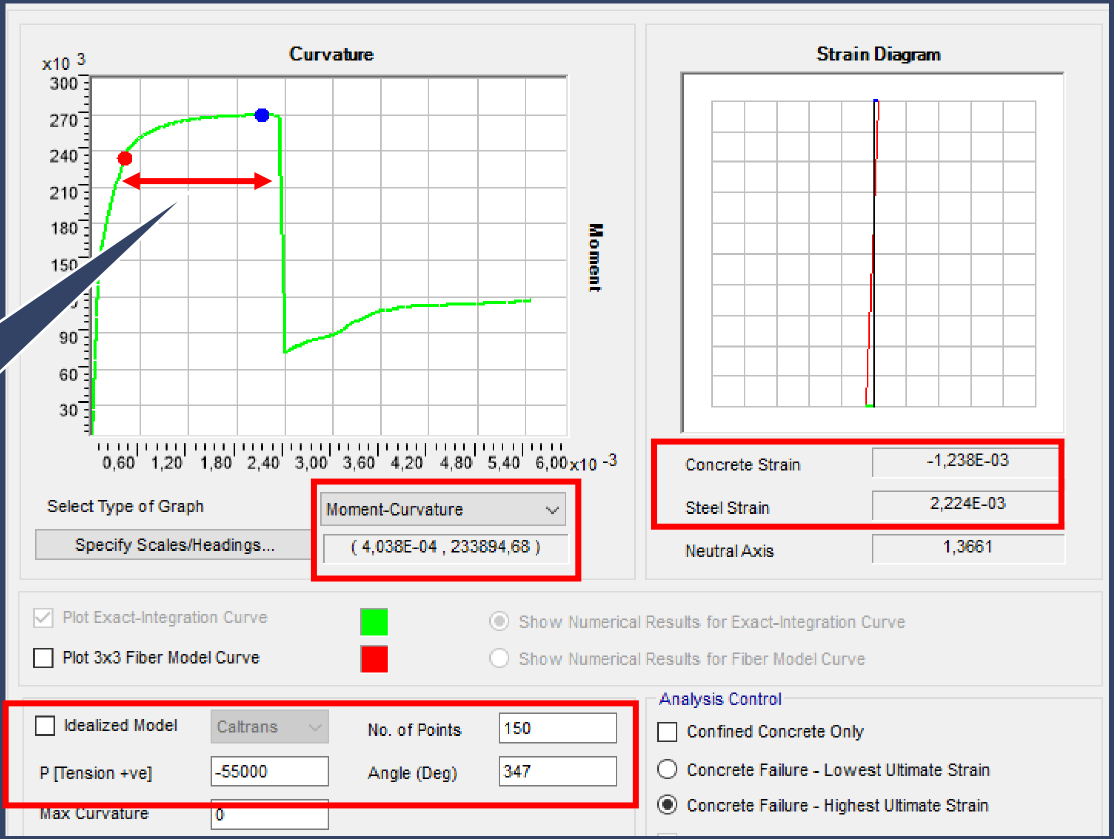


Figure 7: Moment – curvature diagram

2. Numerical example

2.2.2. Core wall as an integral element – Ultimate curvature

Failure Mode I

No spalling of concrete cover
Confined concrete is not activated
Rupture of reinforcement

Failure Mode II

No spalling of concrete cover
Confined concrete is not activated
Crushing of unconfined concrete

Failure Mode III

Spalling of concrete cover
Confined concrete is not fully utilized
Rupture of reinforcement

Failure Mode IV

Spalling of concrete cover
Confined concrete is fully utilized
Crushing of confined concrete

$M_u^{IV} \geq 0.80 \cdot M_u^{II}$? [2]

[2] – Seismic Design, Assessment and Retrofitting of Concrete Buildings – M. Fardis

2. Numerical example

2.2.2. Core wall as an integral element – Ultimate curvature

- Necessary to determine does the section recover after spalling of concrete cover

- Verifications are performed on two separate section models

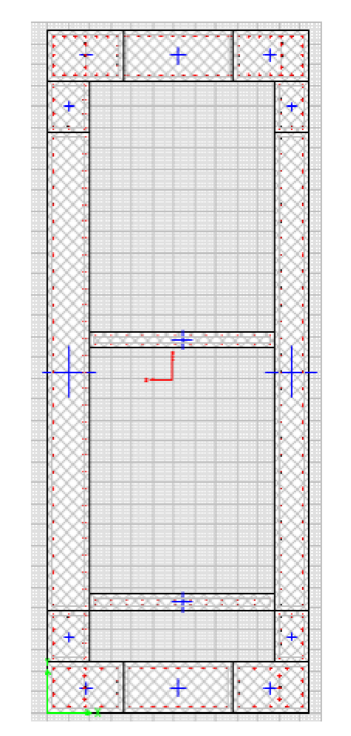


Figure 8: Section for failure modes I and II

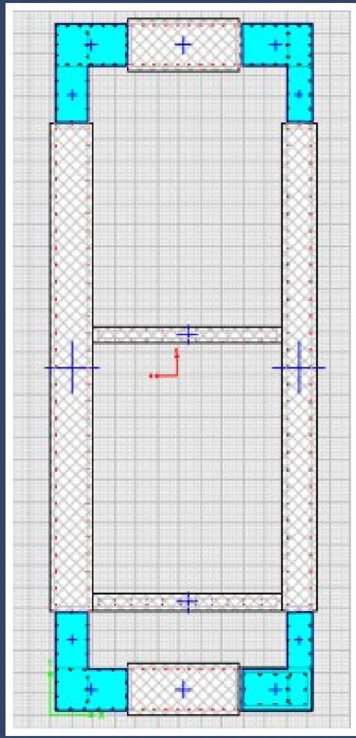


Figure 9: Section for failure modes III and IV

2. Numerical example

2.2.2. Core wall as an integral element – Ultimate curvature

Figure 10: Failure mode II (failure of unconfined concrete)

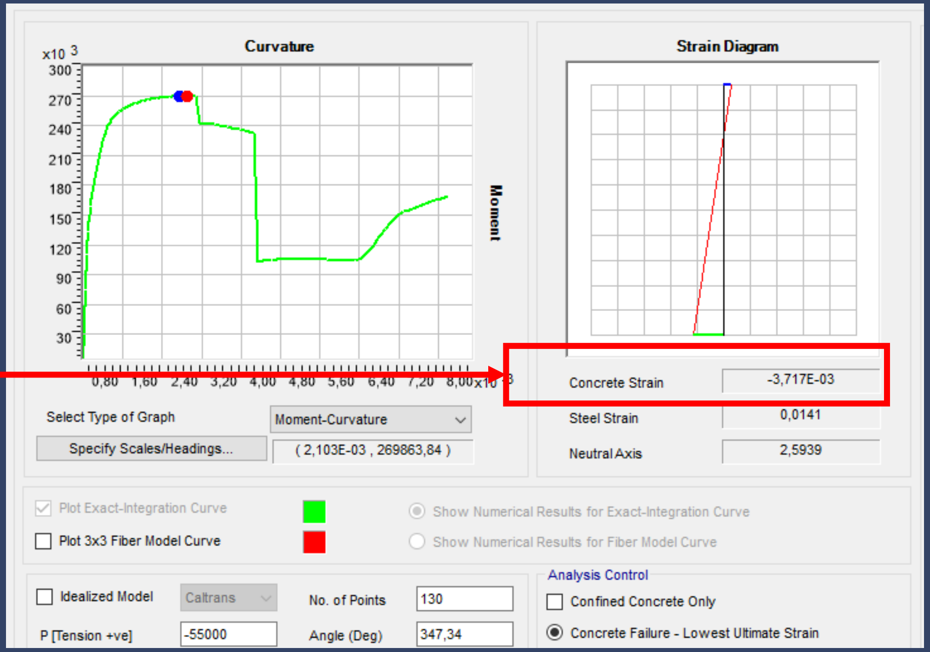
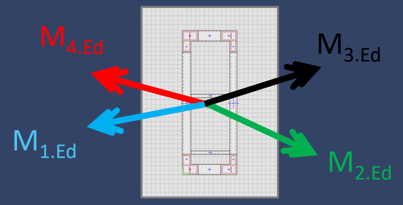


Figure 11: Failure mode IV (failure of confined concrete)

$M_u^{IV} \geq 0,80 \cdot M_u^{II}$? ↔ 269 863kNm ≥ 0,80 ·269 926 kNm ✓

2. Numerical example



2.2.2. Core wall as an integral element – Ultimate curvature

$$\mu_{\phi.cap.4.s} = \frac{\mu_{u.4}{}^{IV}}{\mu_{y.4}} = \frac{2{,}189 \cdot 10^{-3} rad}{3{,}956 \cdot 10^{-4} rad} = 5{,}50$$

$$\mu_{\phi.req} = (2 \cdot 2 - 1) \cdot 1{,}5 = 4{,}5$$

$$\boldsymbol{U_{r.d.4.s} = \frac{\mu_{\phi.req}}{\mu_{\phi.cap.4}{}^{IV}} = \frac{4,50}{5,50} = 81,32\%}$$

$$M_{U.4.s}{}^{IV} = 269\ 863\ \text{kNm}$$

$$\boldsymbol{U_{r.b.4.s} = \frac{M_{Ed.4}}{M_{U.4}{}^{IV}} = \frac{142\ 000\ kNm}{269\ 863\ \text{kNm}} = 52,60\%}$$

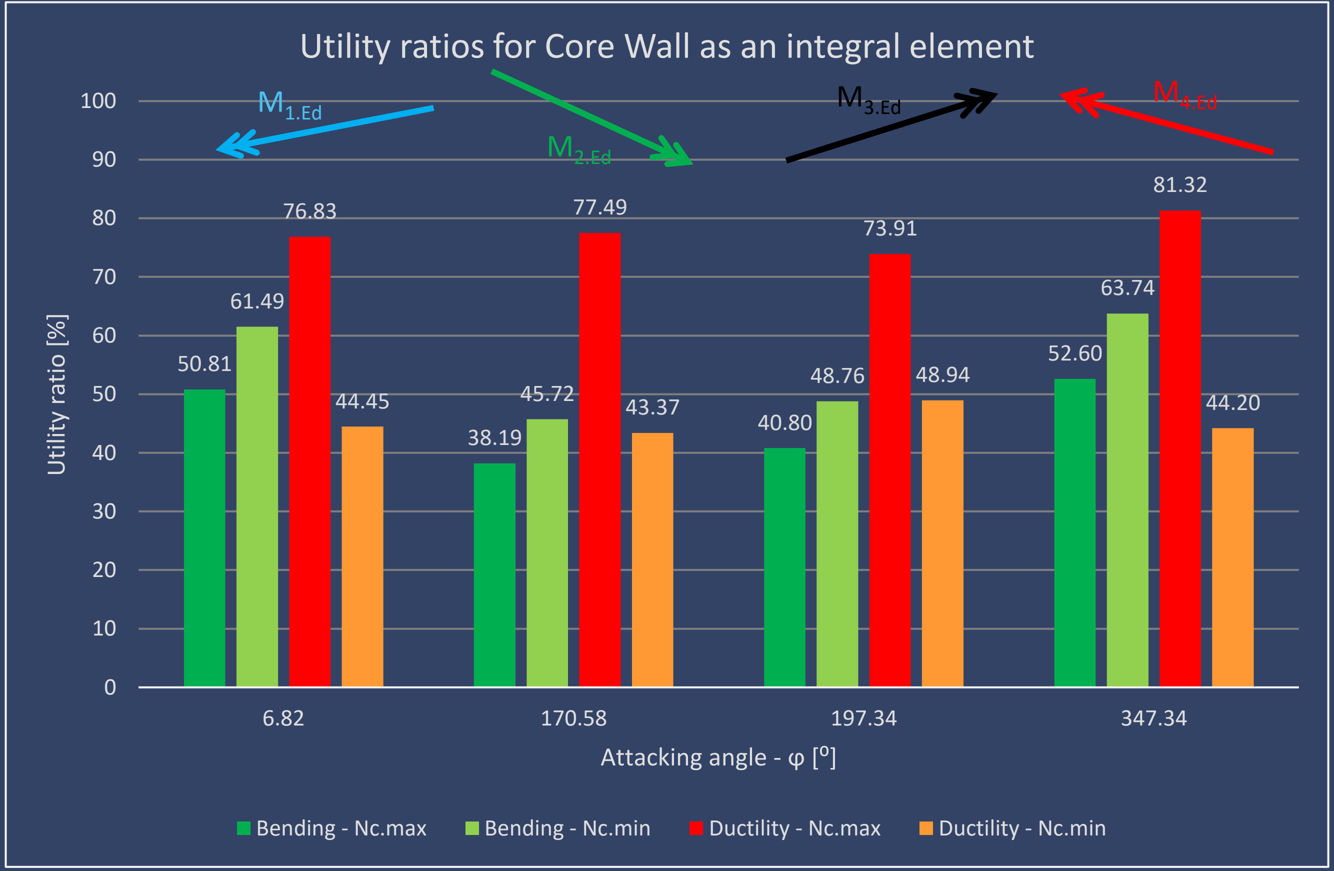


Figure 12: Summary of utility ratios for Core Wall as an integral element

2. Numerical example

2.2.3. Core wall as an integral element – Summary

- Do results differ from the analysis where constituent walls are treated analyzed indenpendently?

- How efficiently confinement effects are utilzed?

- Is this design the optimal one?

2. Numerical example

2.2.3.1. Integral section vs design of constituent sections independently?

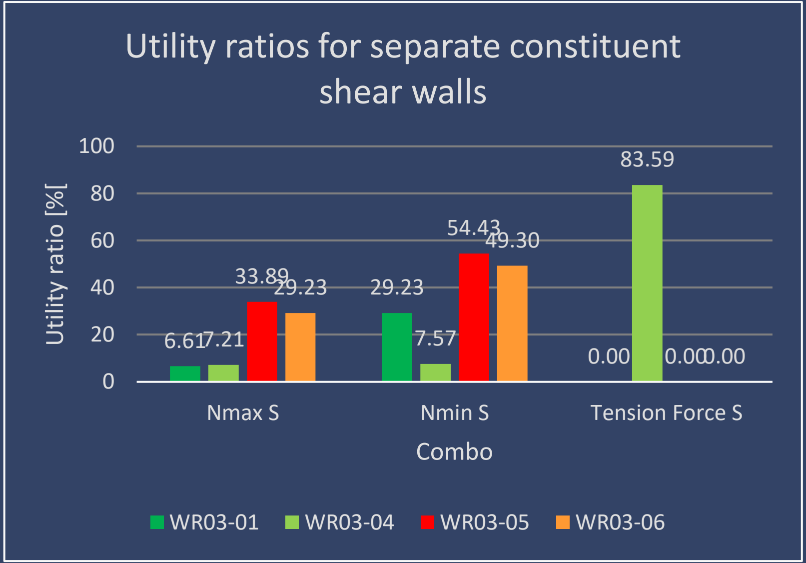


Figure 13: Summary of utility ratios for independent shear walls

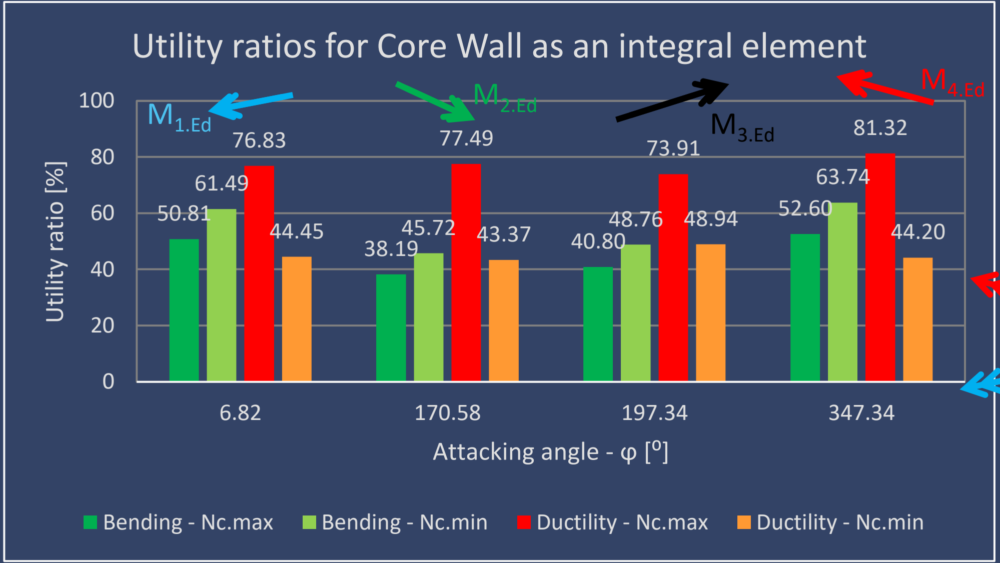


Figure 12: Summary of utility ratios for Core Wall as an integral element

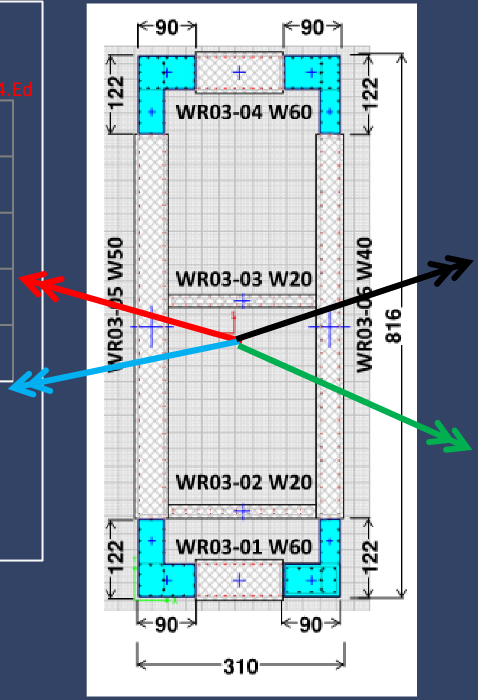


Figure 5: Confined zones and dimensions of core wall

2. Numerical example

2.2.3.1. Integral section vs design of constituent sections independently?

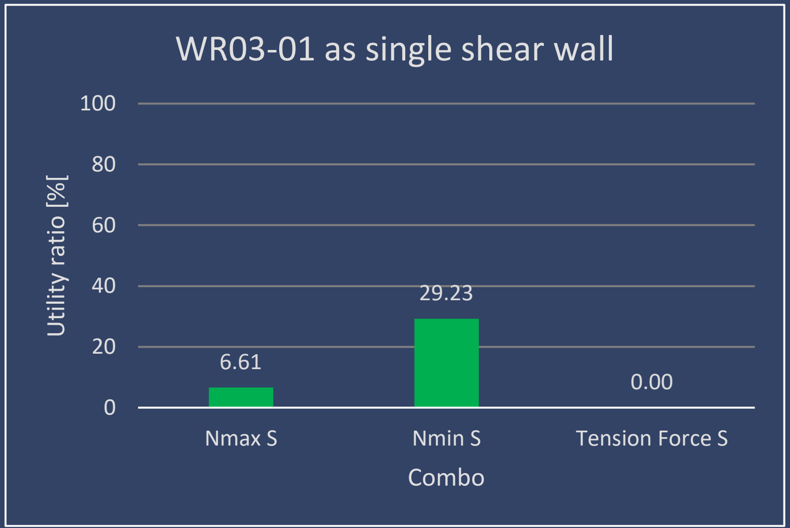


Figure 14: Utility ratio for independent shear wall WR03-01

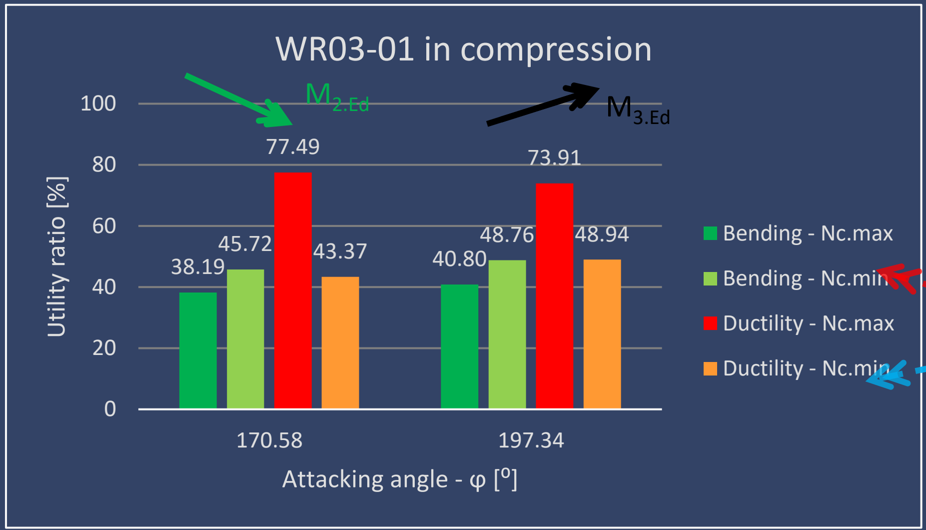


Figure 15: Utility ratios for resultant moments $M_{2.Ed}$ and $M_{3.Ed}$

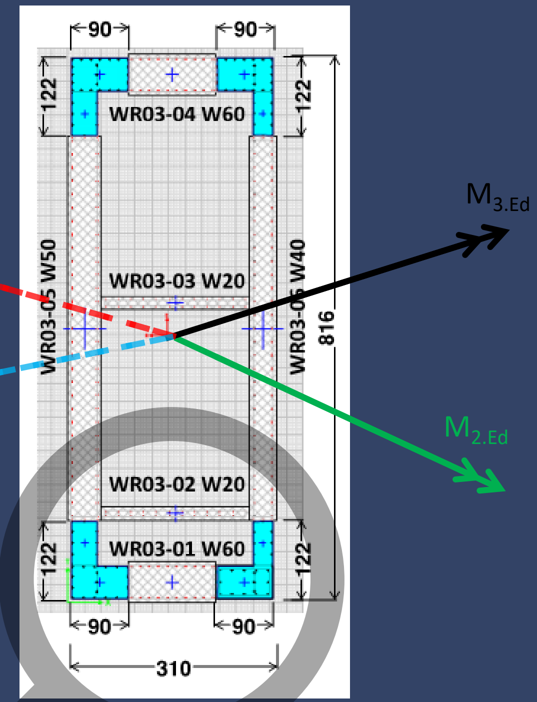


Figure 5: Confined zones and dimensions of core wall

Distribution of internal forces is vastly different if core wall is treated as an integral section!

2. Numerical example

2.2.3.2. How efficiently confinement effects are utilized?

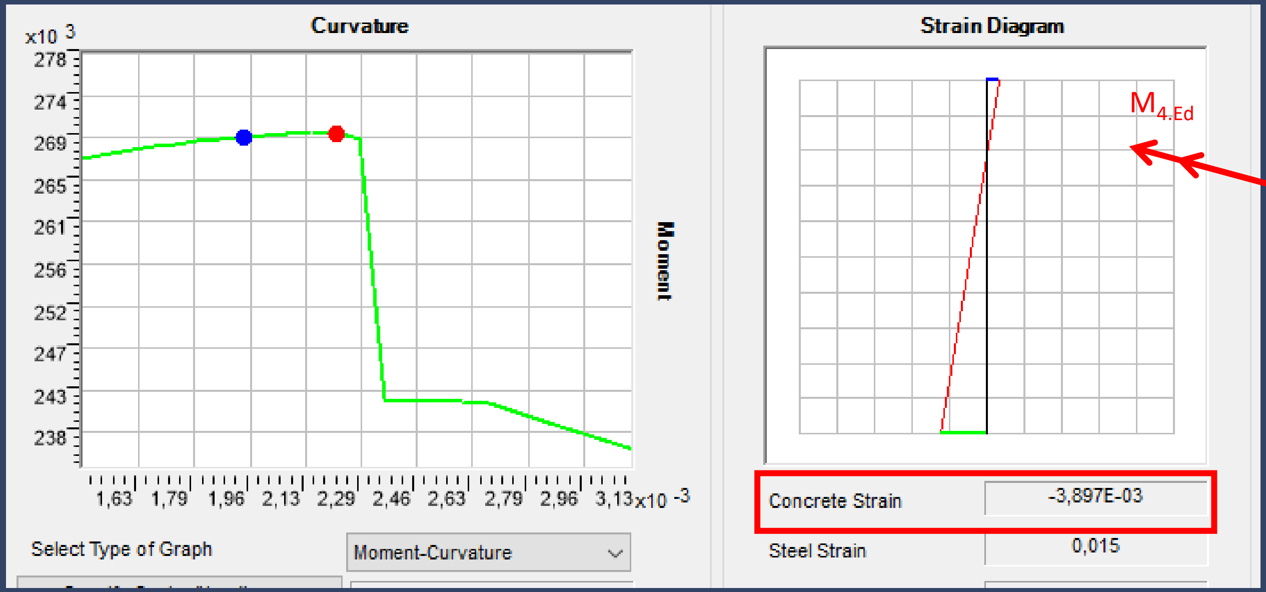


Figure 16: Moment-curvature plot for $M_{4.Ed}$

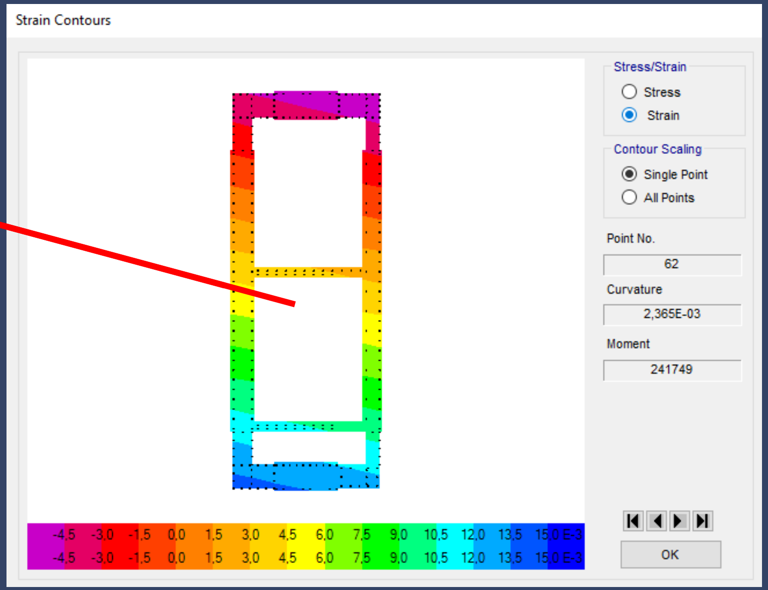


Figure 17: Strain distribution for $M_{4.Ed}$

2. Numerical example

2.2.3.2. How efficiently confinement effects are utilized?

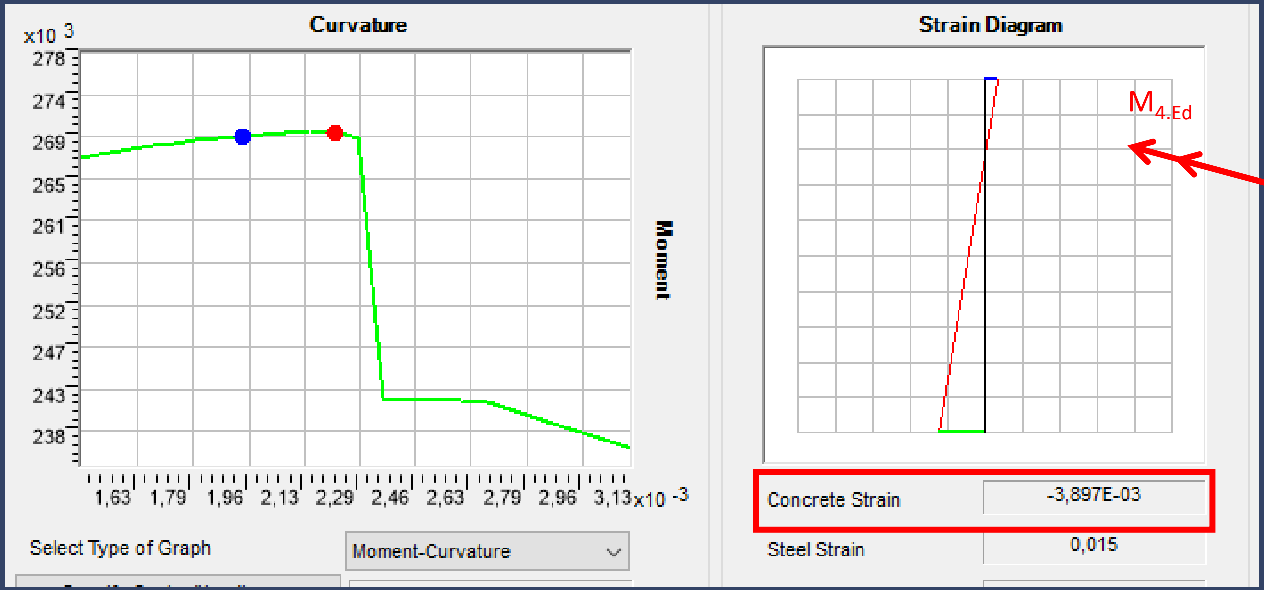


Figure 16: Moment-curvature plot for $M_{4.Ed}$

Figure 18: Stress distribution for $M_{4.Ed}$

2. Numerical example

2.2.3.2. How efficiently confinement effects are utilized?

$\varepsilon_{cu.c.ut} = 3{,}897 \cdot 10^{-3}$

$\varepsilon_{cu.c} = 9{,}362 \cdot 10^{-3}$

$$\boldsymbol{U_{r.\varepsilon}} = \frac{\varepsilon_{cu.c.ut}}{\varepsilon_{cu.c}} = \frac{3{,}897 \cdot 10^{-3}}{9{,}362 \cdot 10^{-3}} = \mathbf{41{,}36\%}$$

Poor use of confinement effects!

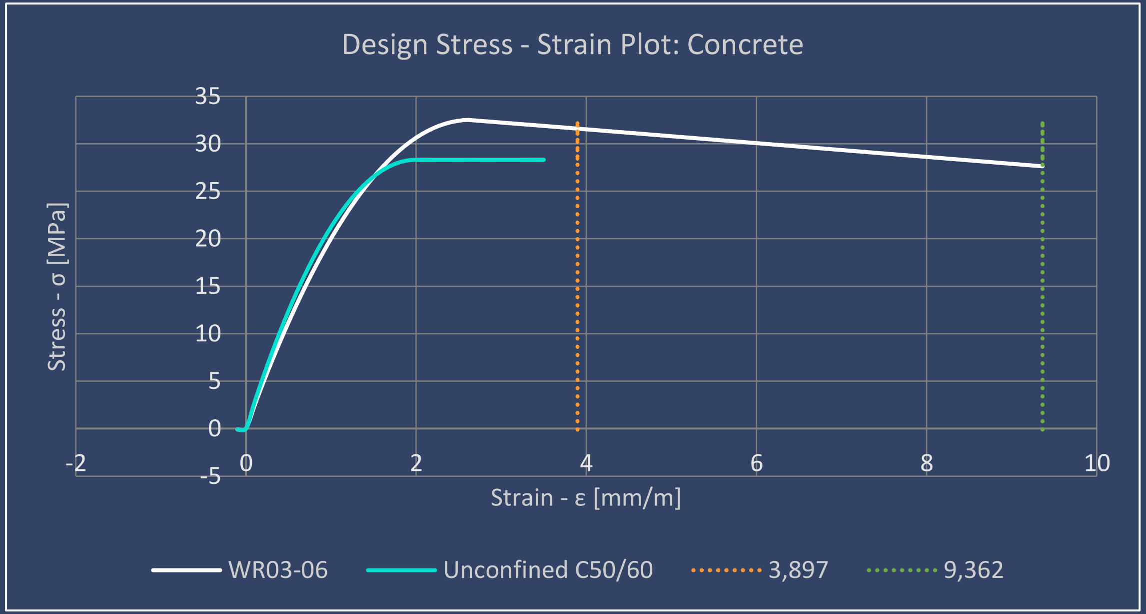


Figure 19: Utilization of confinement effects

2. Numerical example

2.2.3.3. Should constituent walls be treated as single shear walls?

?

YES	NO
It is convenient and easy	Design code [1] requires 5.4.3.4.1 (4) to be applied
Design **(IN THIS CASE)** is still satisfactory	Design might not be satisfactory in general case
	Ineadequate use of beneficial confinement effects
	Ineadequate layout of confinement zones
	Vastly different distruibution of internal forces

[1] – EN1998-1:2004

3. Optimization

How to find optimized reinforcement layout?

Local analysis SAP2000			
$M_{1.Ed}$	$M_{2.Ed}$	$M_{3.Ed}$	$M_{4.Ed}$
[kNm]	[kNm]	[kNm]	[kNm]
139000	**101000**	105000	**142000**
φ_1	φ_2	φ_3	φ_4
[°]	[°]	[°]	[°]
6,82	**170,58**	197,30	**347,34**
Δ			
±6,82	**±9,42**	**±17,3**	**±12,66**

Table 4: Acting bending moments on concrete core

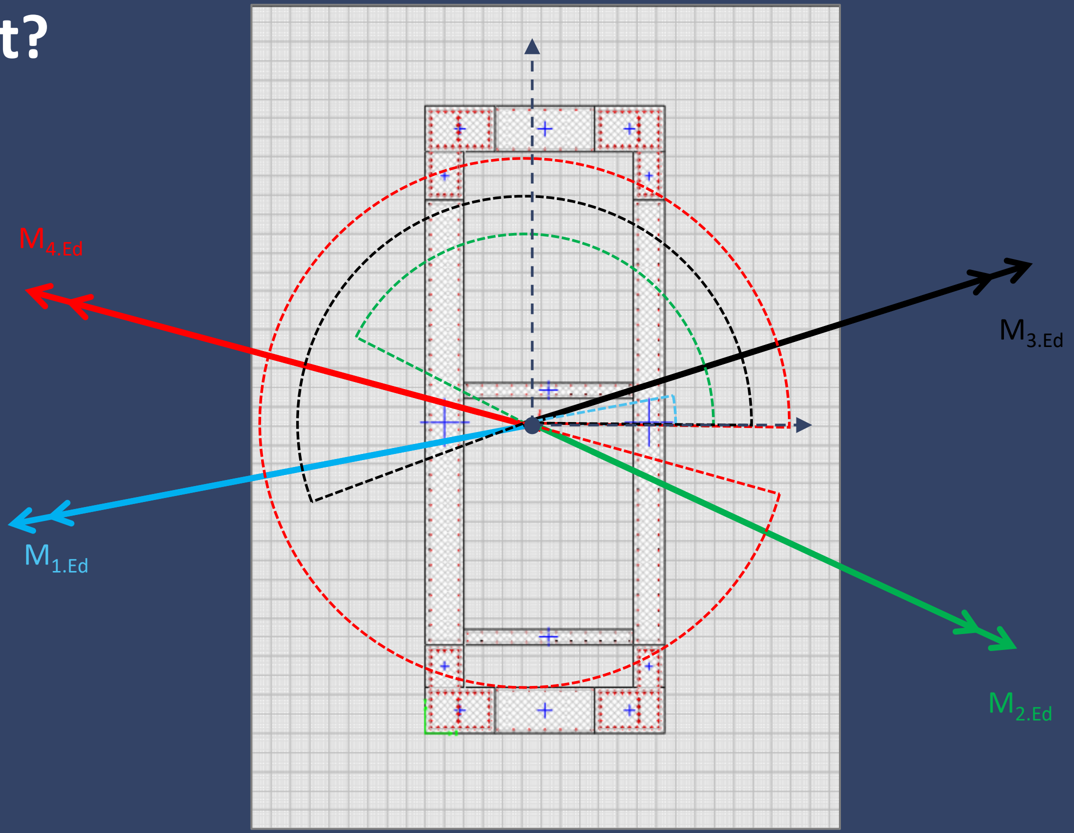


Figure 6: Resultant biaxial bending moments

Almost uniaxial bending of concrete core

3. Optimization

Analogy with single shear wall:

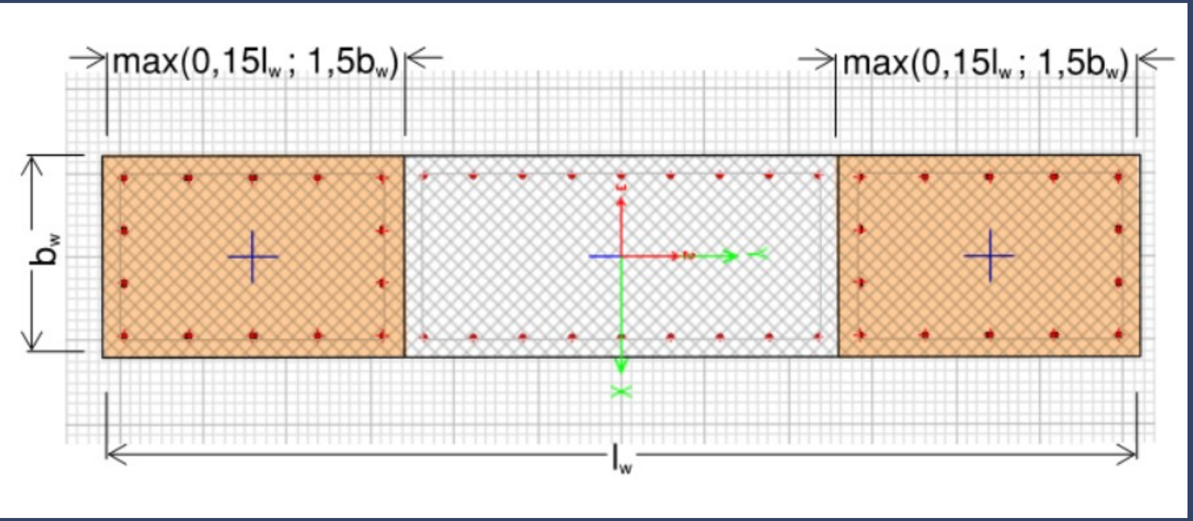


Figure 20: Minimal confined areas for single shear wall

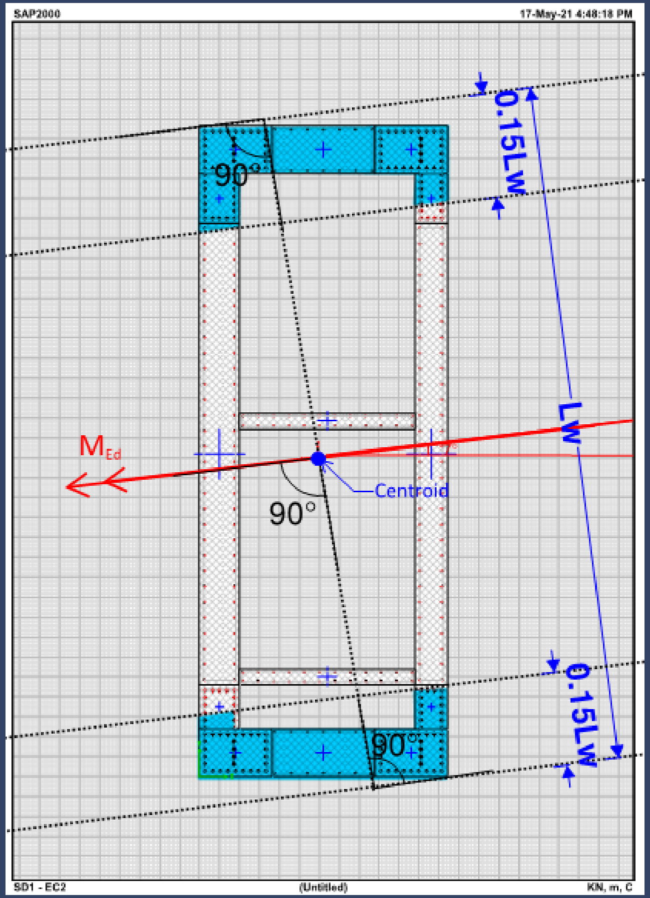


Figure 21: Proposed new layout of confined zones

3. Optimization

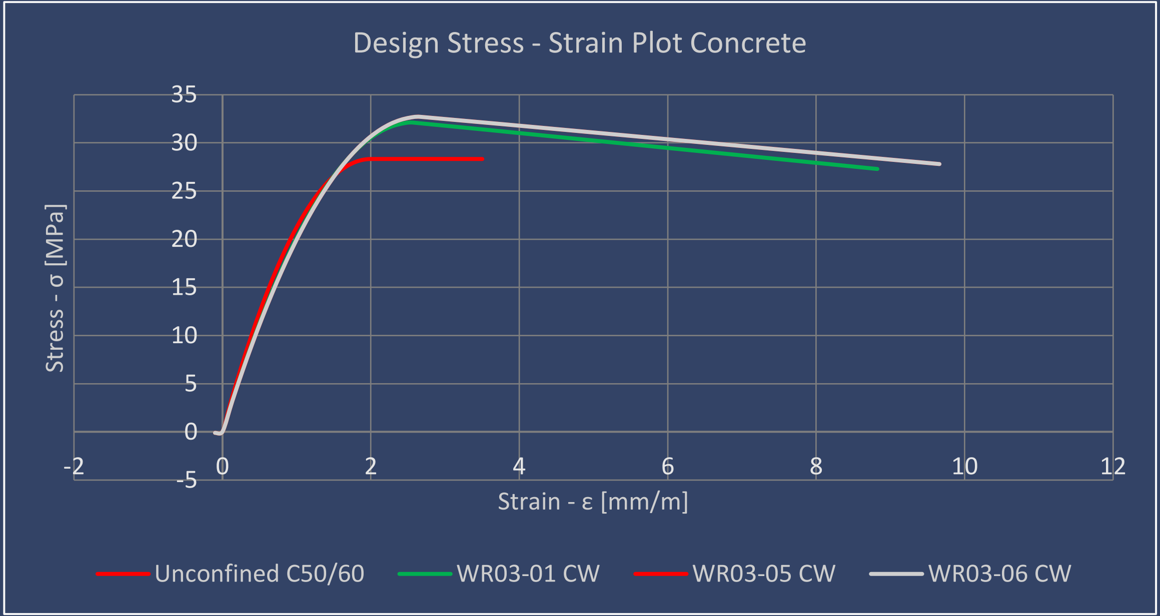


Figure 22: Updated confined concrete properties

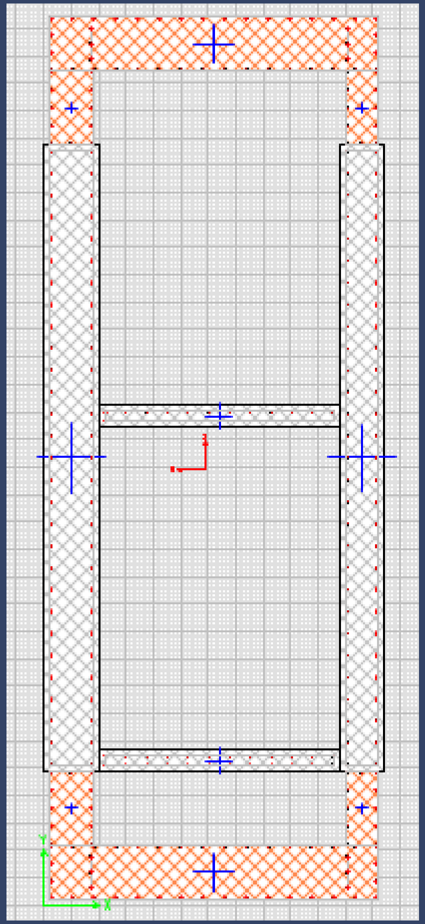


Figure 23: New layout of confined zones

3. Optimization

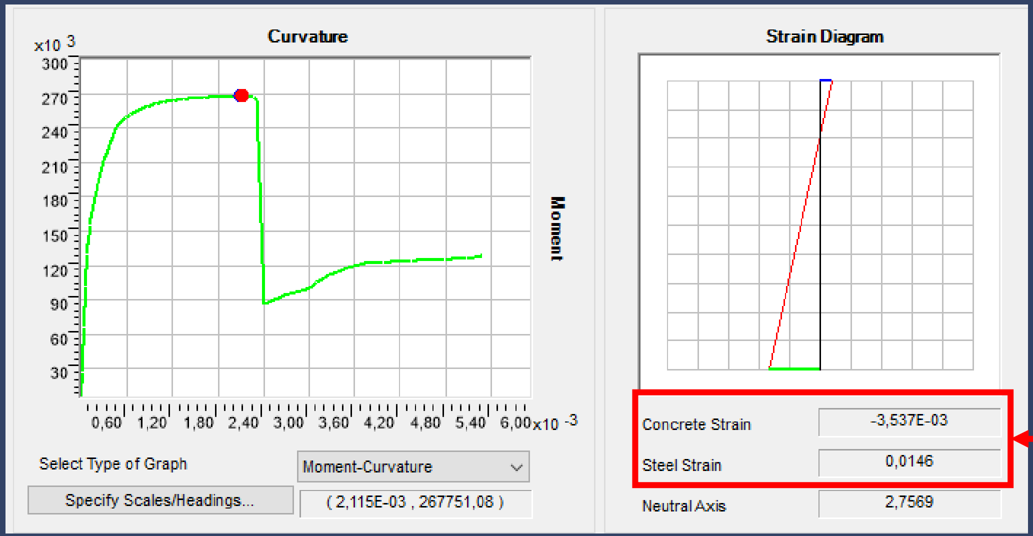


Figure 24: Failure mode II (failure of unconfined concrete)

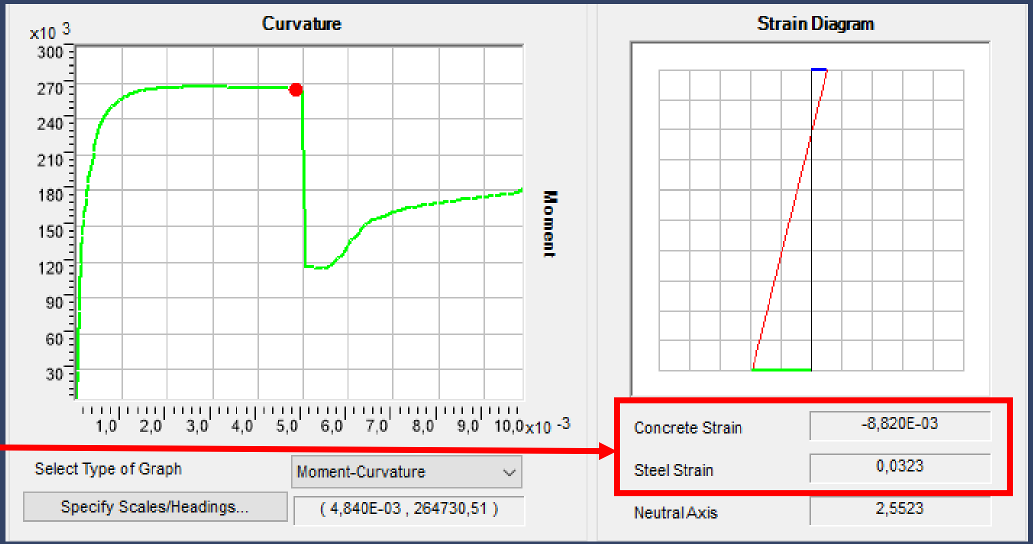
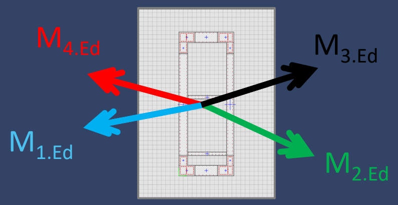


Figure 25: Failure mode IV (failure of confined concrete)

$M_u^{IV} \geq 0{,}80 \cdot M_u^{II}$? ↔ 267 430kNm ≥ 0,80 ·267 751 kNm ✓

3. Optimization



$$\mu_{\phi.cap.4.r} = \frac{{\mu_{u.4}}^{IV}}{\mu_{y.4}} = \frac{4{,}840 \cdot 10^{-3} rad}{3{,}846 \cdot 10^{-4} rad} = 12{,}58$$

$$\mu_{\phi.req} = (2 \cdot 2 - 1) \cdot 1{,}5 = 4{,}5$$

$$\boldsymbol{U_{r.d.4.r} = \frac{\mu_{\phi.req}}{{\mu_{\phi.cap.4}}^{IV}} = \frac{4,50}{12,58} = 35,77\%}$$

$${M_{U.4.r}}^{IV} = 264\ 728\ \text{kNm}$$

$$\boldsymbol{U_{r.b.4,r} = \frac{M_{Ed.4}}{{M_{U.4}}^{IV}} = \frac{142\ 000\ kNm}{264\ 728\ \text{kNm}} = 53,64\%}$$

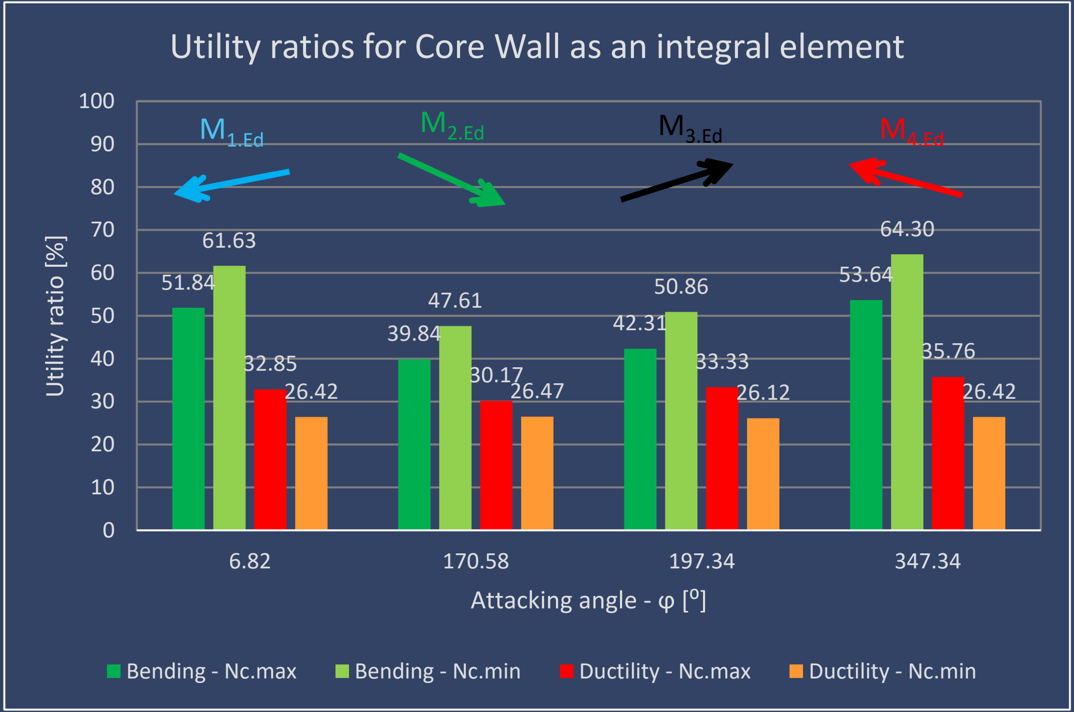


Figure 26: Summary of utility ratios for Core Wall as an integral element (revised layout)

3. Optimization

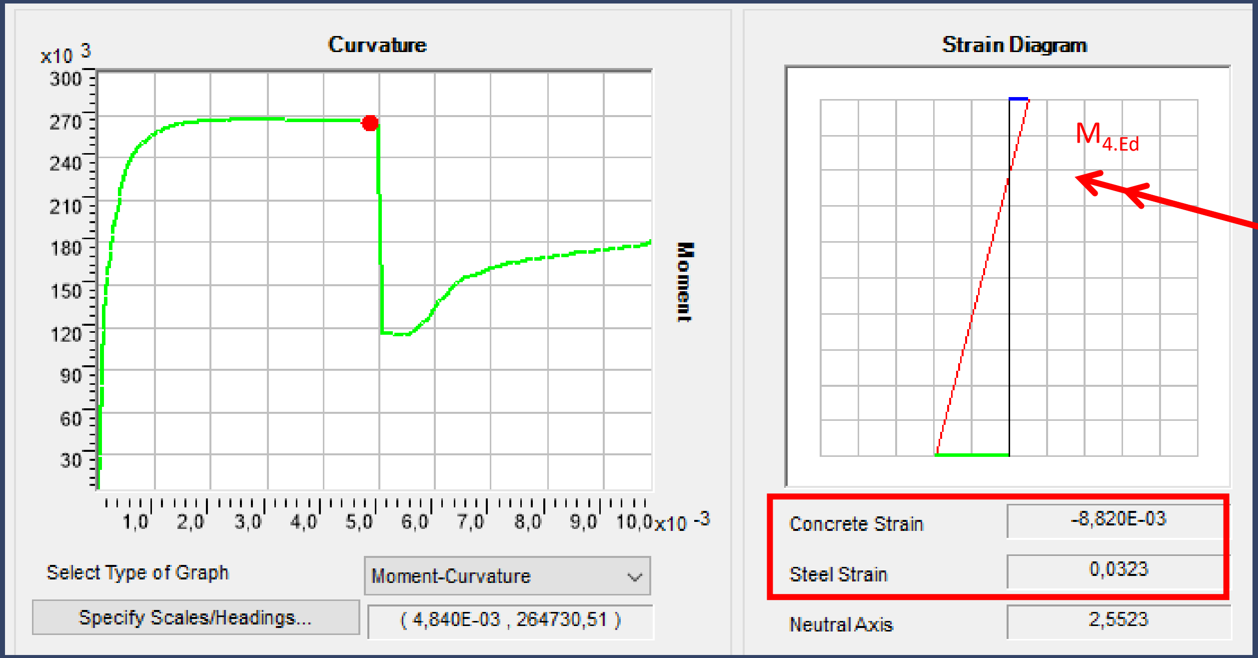


Figure 27: Moment-curvature plot for $M_{4.Ed}$

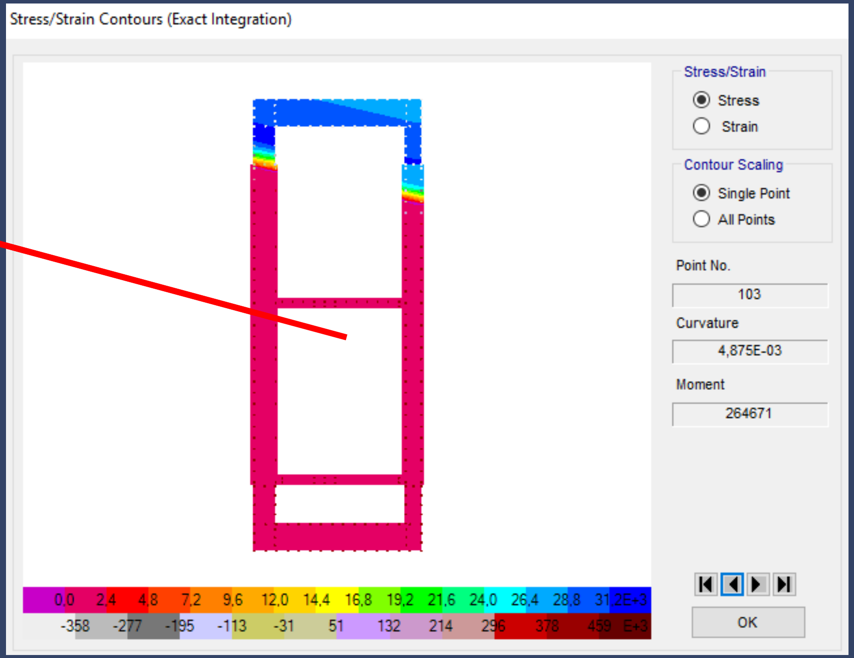


Figure 28: Stress distribution for $M_{4.Ed}$

3. Optimization

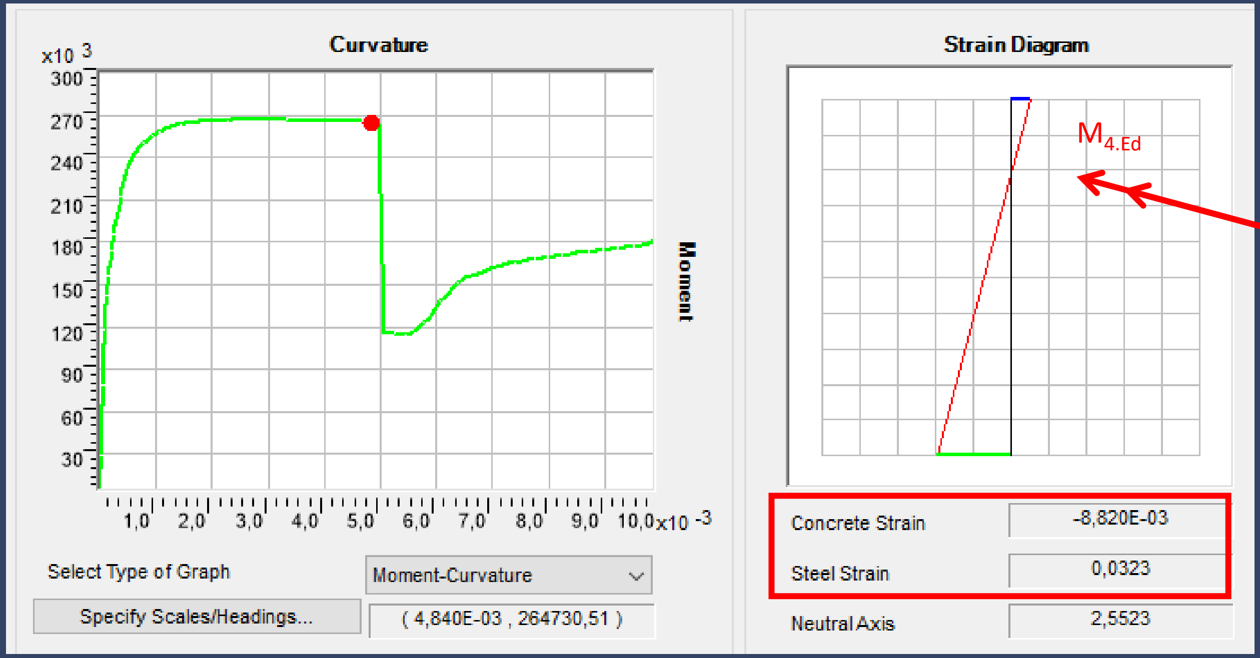


Figure 29: Moment-curvature plot for $M_{4.Ed}$

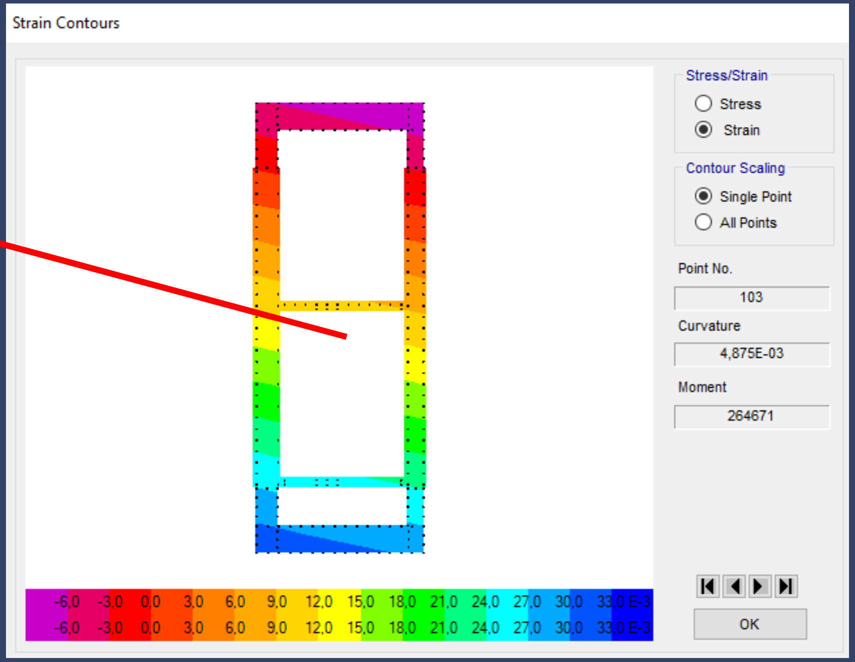
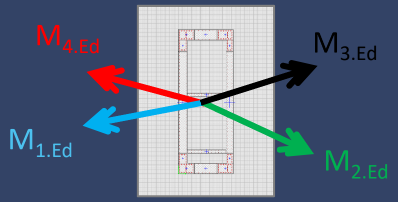


Figure 30: Strain distribution for $M_{4.Ed}$

3. Optimization



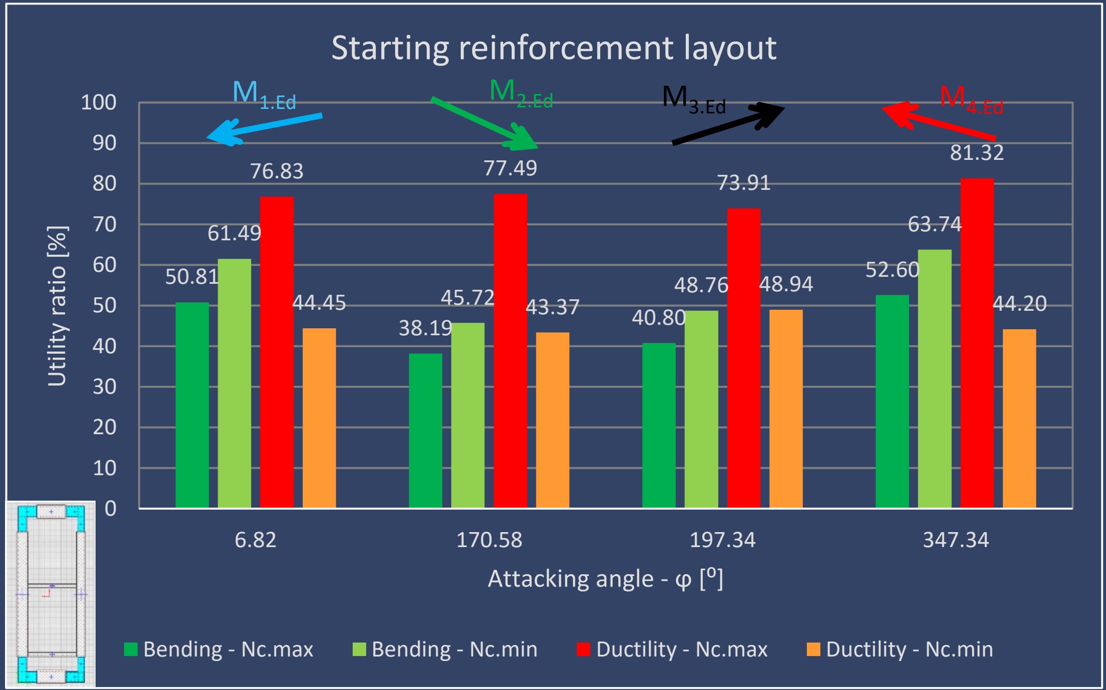


Figure 12: Summary of utility ratios for Core Wall as an integral element (starting layout)

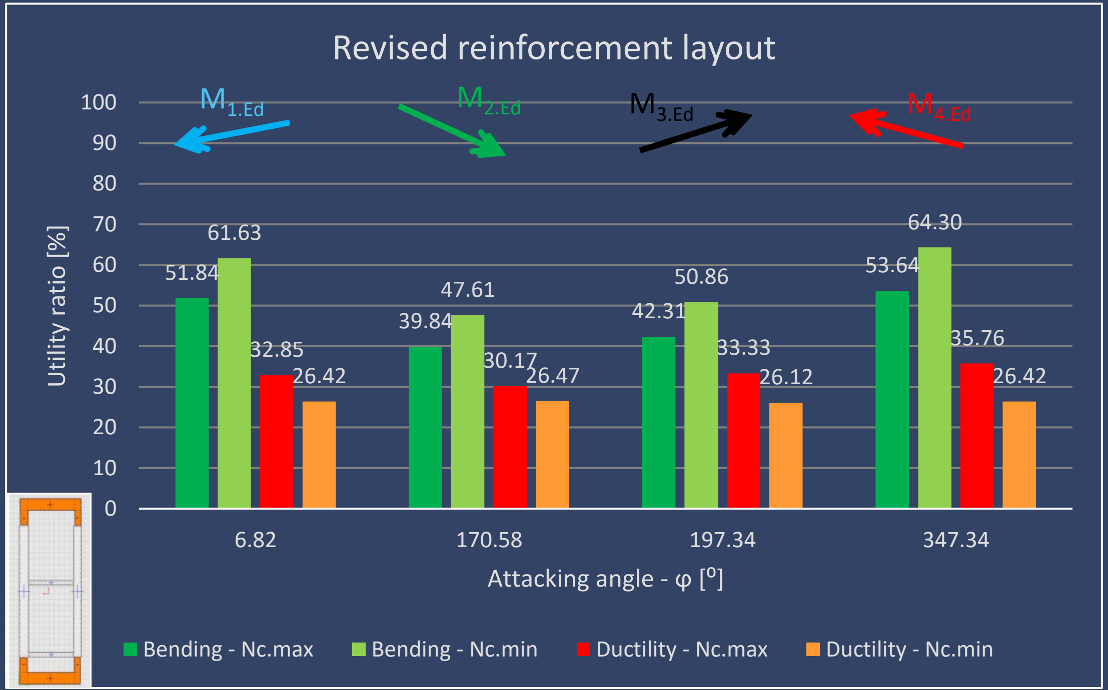
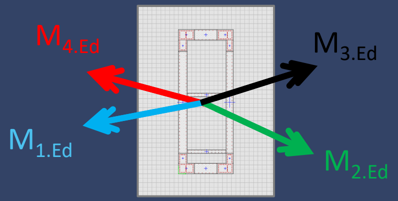


Figure 26: Summary of utility ratios for Core Wall as an integral element (revised layout)

3. Optimization



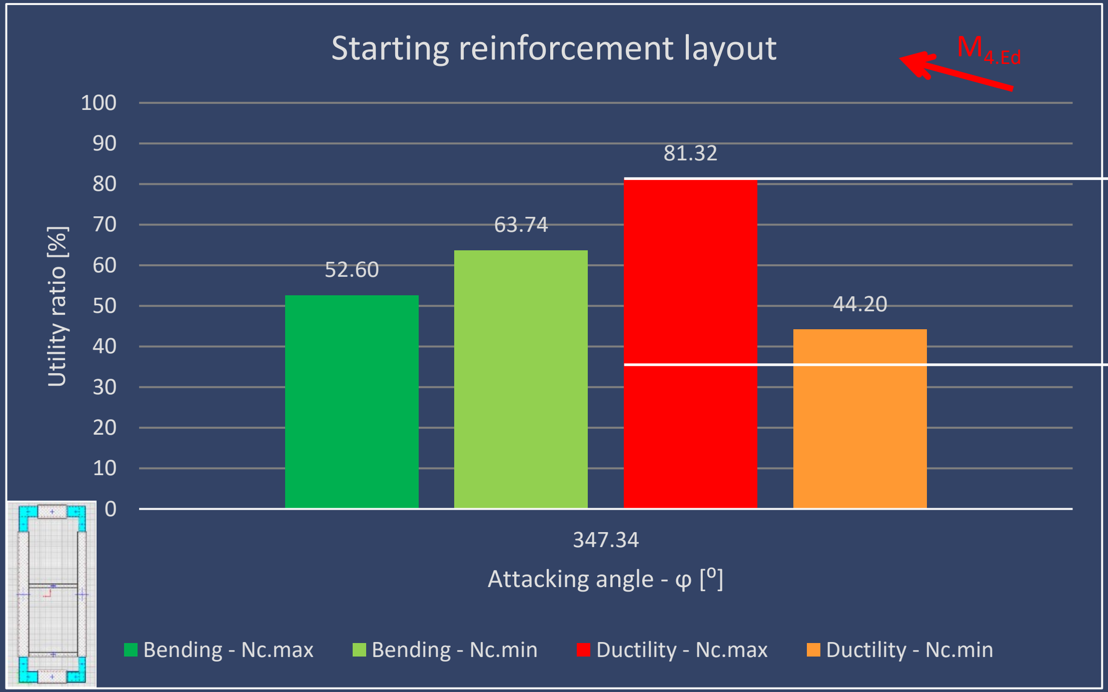


Figure 31: Utility ratios for Core Wall as an integral element (starting layout) – $M_{4.Ed}$

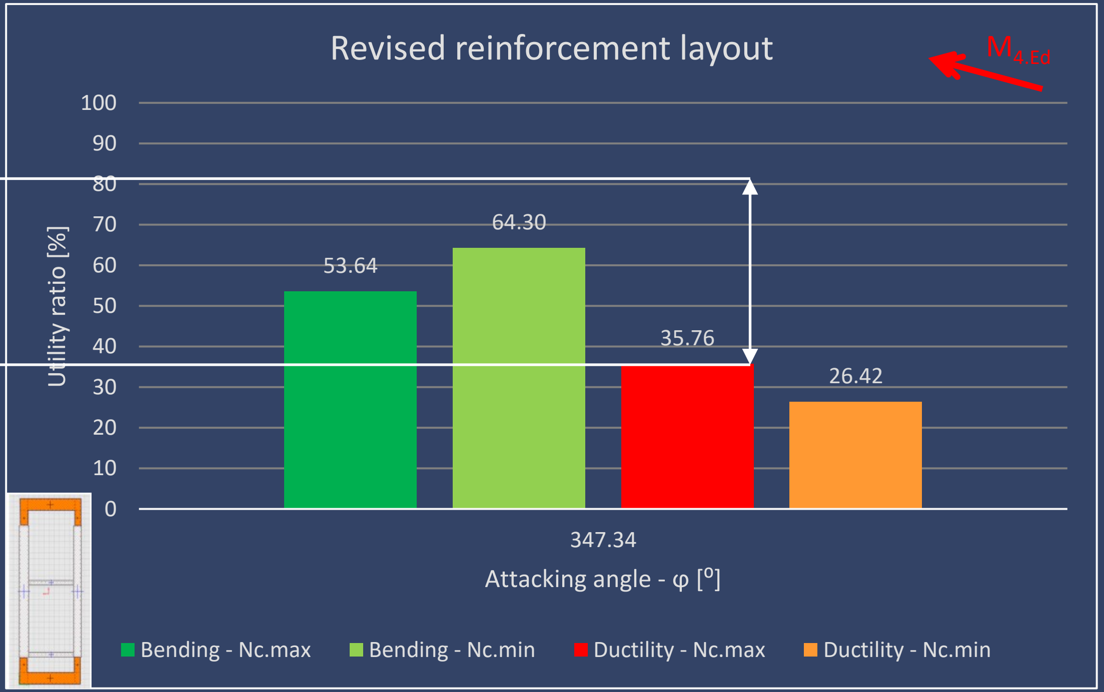


Figure 32: Utility ratios for Core Wall as an integral element (revised layout) - $M_{4.Ed}$

3. Optimization

At what expense this improvement in behaviour is achieved?

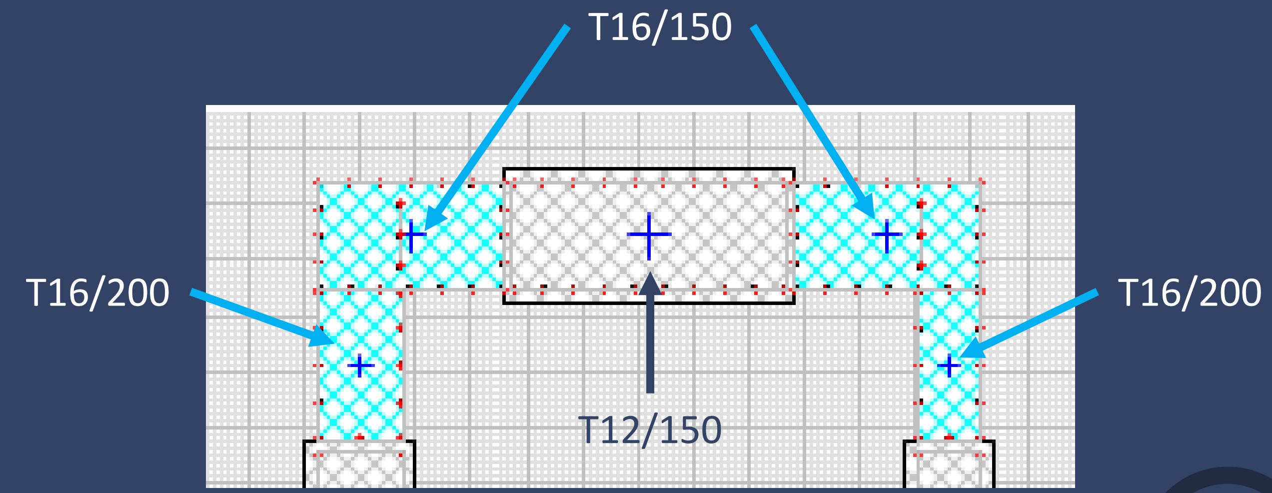
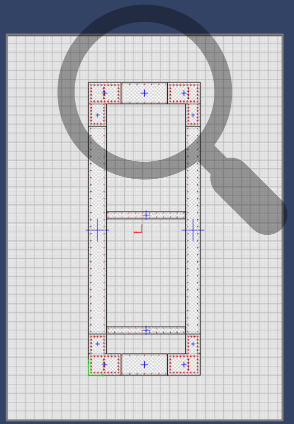


Figure 33: Starting layout of reinforcement



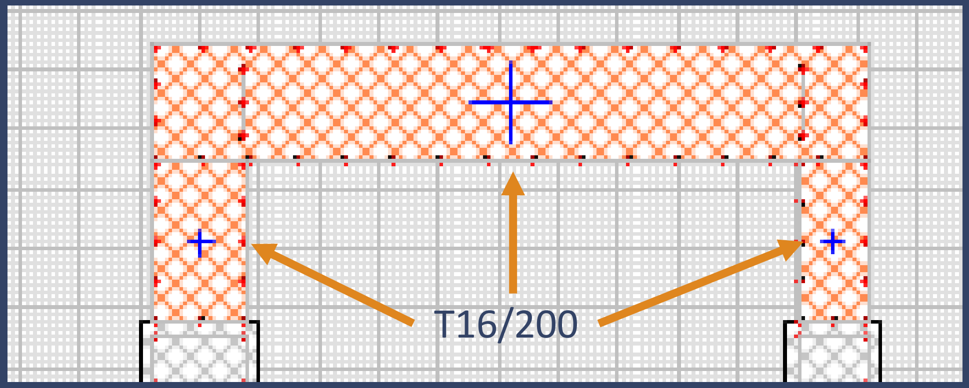


Figure 34: Revised layout of reinforcement

$$As_s = 65T12 + 20T12 = 153{,}31cm^2$$

$$\Delta_A = \frac{As_r}{As_s} = \frac{128{,}68cm^2}{153{,}31cm^2} = 83{,}93\%$$

$$\boldsymbol{\delta_A = \Delta_A - 1 = -16{,}07\%}$$

$$As_r = 64T16 = 128{,}68cm^2$$

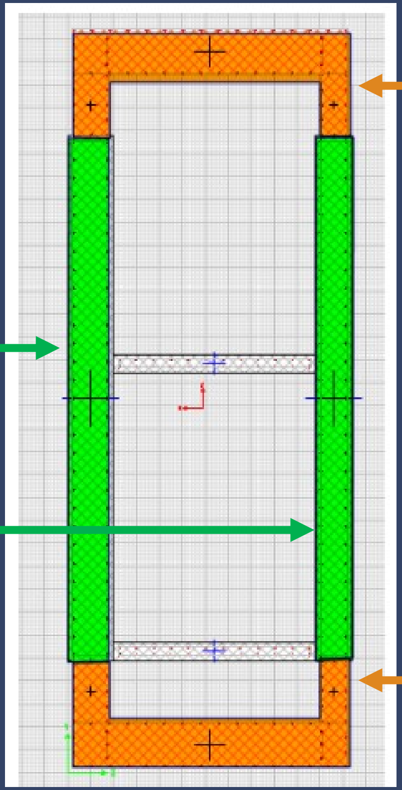
$$\Delta_\mu = \frac{\mu_{\phi.cap.4.r}}{\mu_{\phi.cap.4.s}} = \frac{12.58}{5{,}50} = 228{,}73\%$$

$$\boldsymbol{\delta_\mu = \Delta_\mu - 1 = 128{,}73\%}$$

3. Optimization

Special considerations - Openings?

- From the strain distruibution it is easy to conclude which areas are most highly utilized



3. Optimization

Special considerations - Openings?

5.2.1 (1) [1]

5.4.3.4.1 (4) [

5.4.3.4.2 (5) [

Summary

!

Ductile wall:

Ductile wall is an element fixed at its base so that the relative rotation of this base with respect to the rest of the structural system is prevented, and that is designed and detailed to dissipate energy ***in a flexural plastic hinge zone free of openings or large perforations, just above its base.***

[1] – EN1998-1:2004

3. Optimization

Special considerations - Openings?

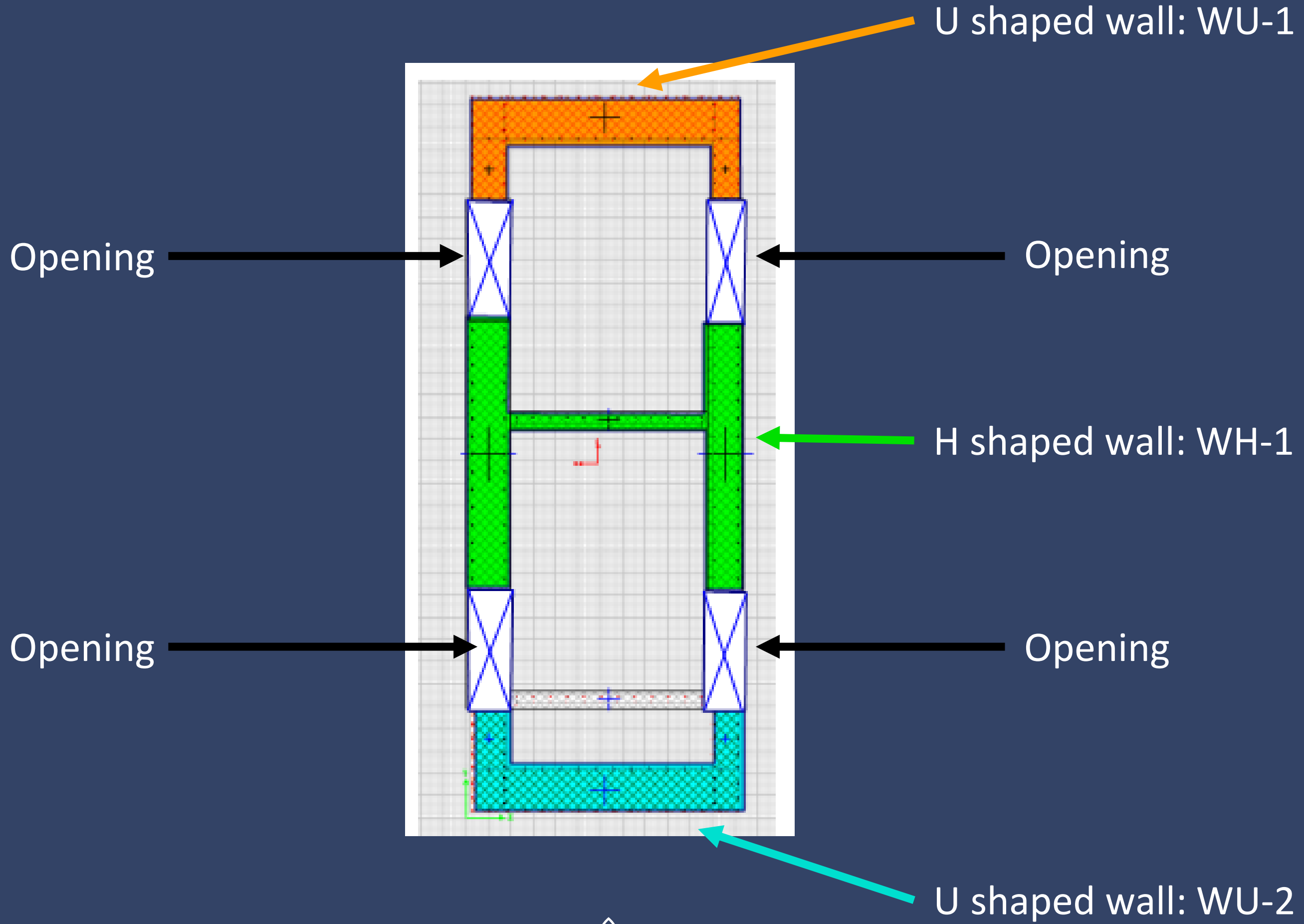
"…knowledge of their (composite walls) behavior under cyclic biaxial bending and shear is very limited, and that the rules used for their dimensioning and detailing still lack a sound basis… ***Designers should opt for fairly simple geometries…"*** [2]

*"…**openings should be arranged at every floor at a very regular pattern**, turning the wall into a coupled one, with the lintels between the openings serving and designed as coupling beams…"* [2]

[2] – Seismic Design, Assessment and Retrofitting of Concrete Buildings – M. Fardis

3. Optimization

Special considerations - Openings?



4. Conclusions

1. Distribution of internal forces is vastly different if constitutent walls are treated separately

"…The nonlinearities in a section analysis at the ULS may lead to a distribution of strains and stresses in the actual composite section ***which is vastly different from that in the artificially articulated section under the M_y-M_z-N triplets of its individual parts****. So, these triplets should be composed into a single one for the entire wall section.."* [2]

[2] – Seismic Design, Assessment and Retrofitting of Concrete Buildings – M. Fardis

4. Conclusions

2. No correlation between behaviour of single sheer walls and concrete core as an integral section

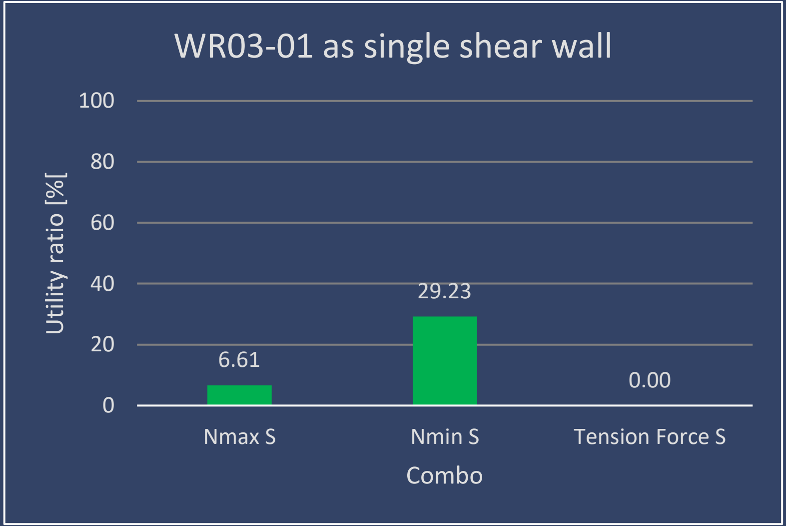


Figure 14: Utility ratio for independent shear wall WR03-01

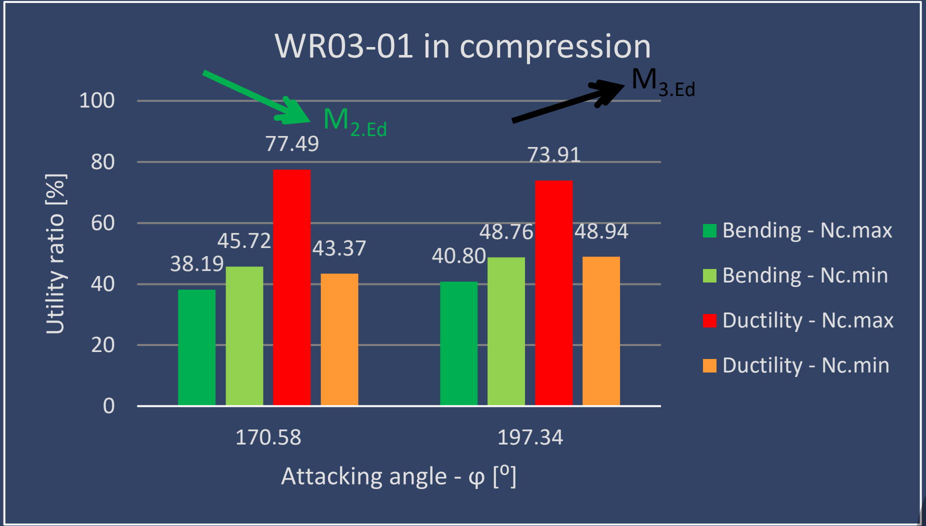


Figure 15: Utility ratios for resultant moments $M_{2.Ed}$ and $M_{3.Ed}$

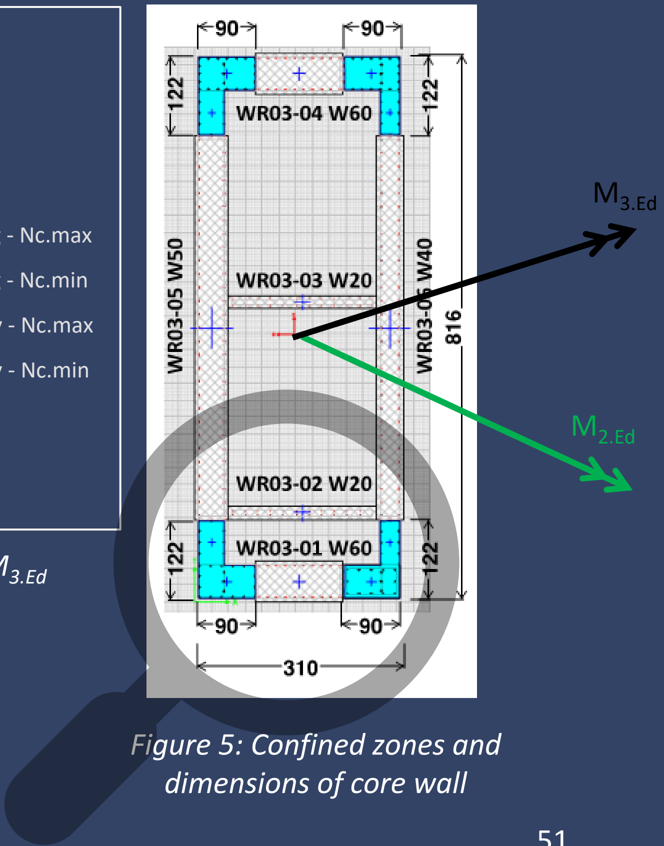
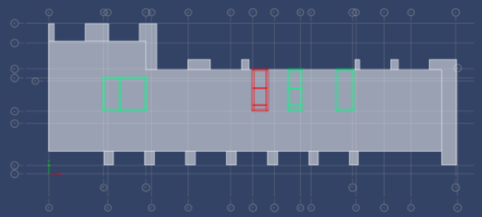
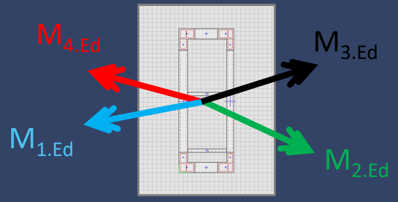


Figure 5: Confined zones and dimensions of core wall

4. Conclusions





3. There is no evidence to prove that design of constituent walls as single sheer walls is on safe side! **On the contrary it is probably not!!!**

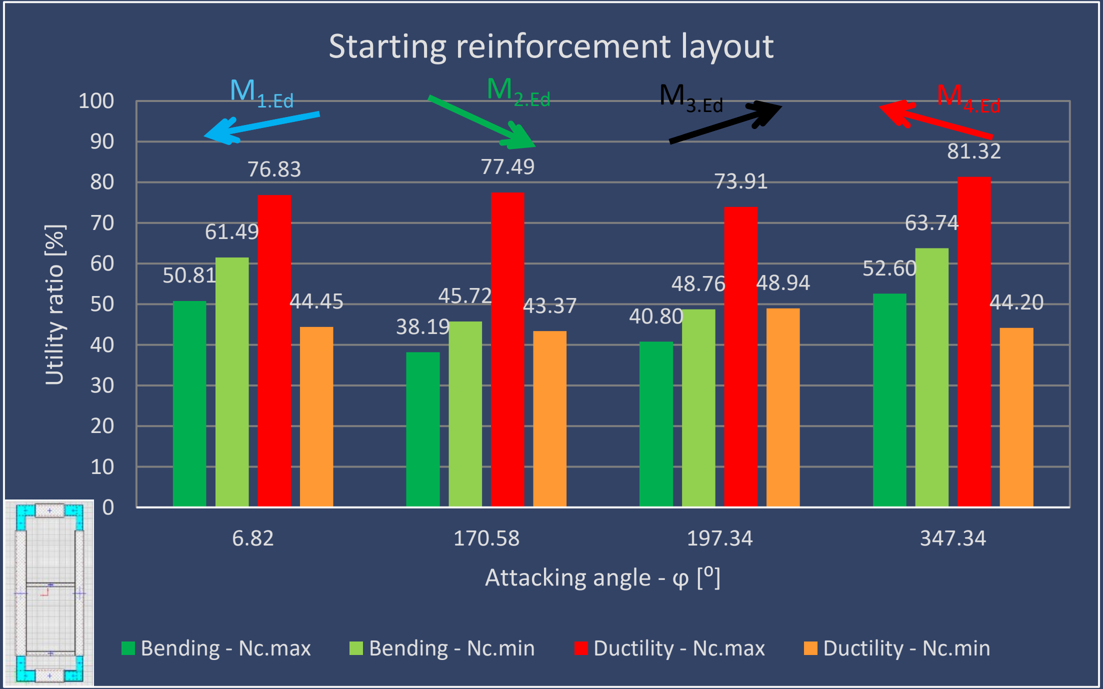


Figure 12: Summary of utility ratios for Core Wall as an integral element (starting layout)

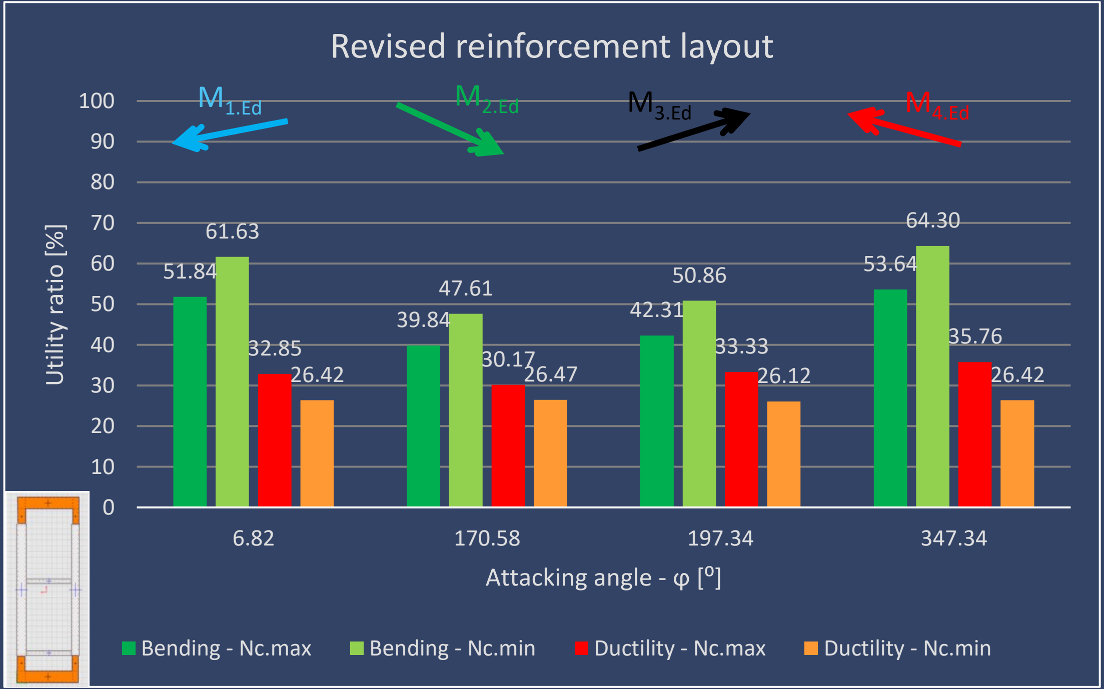


Figure 26: Summary of utility ratios for Core Wall as an integral element (revised layout)