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Multi layered shotcrete design for tunnel construction

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Shotcrete for Underground Support XIII

Irsee/Germany, 4th September 2017,

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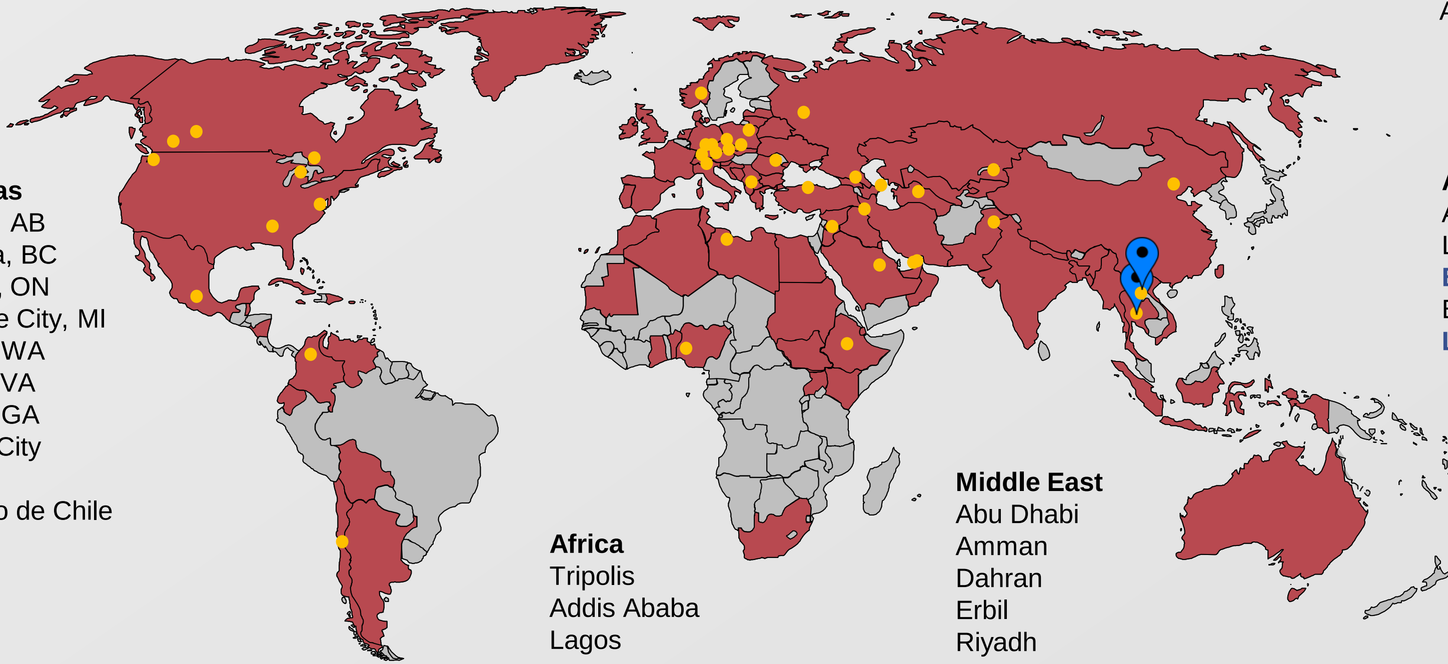

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Project experience
Office locations

Structural Design of Shotcrete Lining

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- ❑ up to the 1970's design was based mainly on **experience gathered throughout the construction** and some **simplified analyses**

Today:

- ❑ Accurate **estimation of deformations and stress state** in the shotcrete lining
- ❑ Consideration of **time** and **construction sequence**
- ❑ Applying simplified **time dependent material laws for shotcrete**

⇨⇨⇨ **Eurocode 2 (EC 2)**

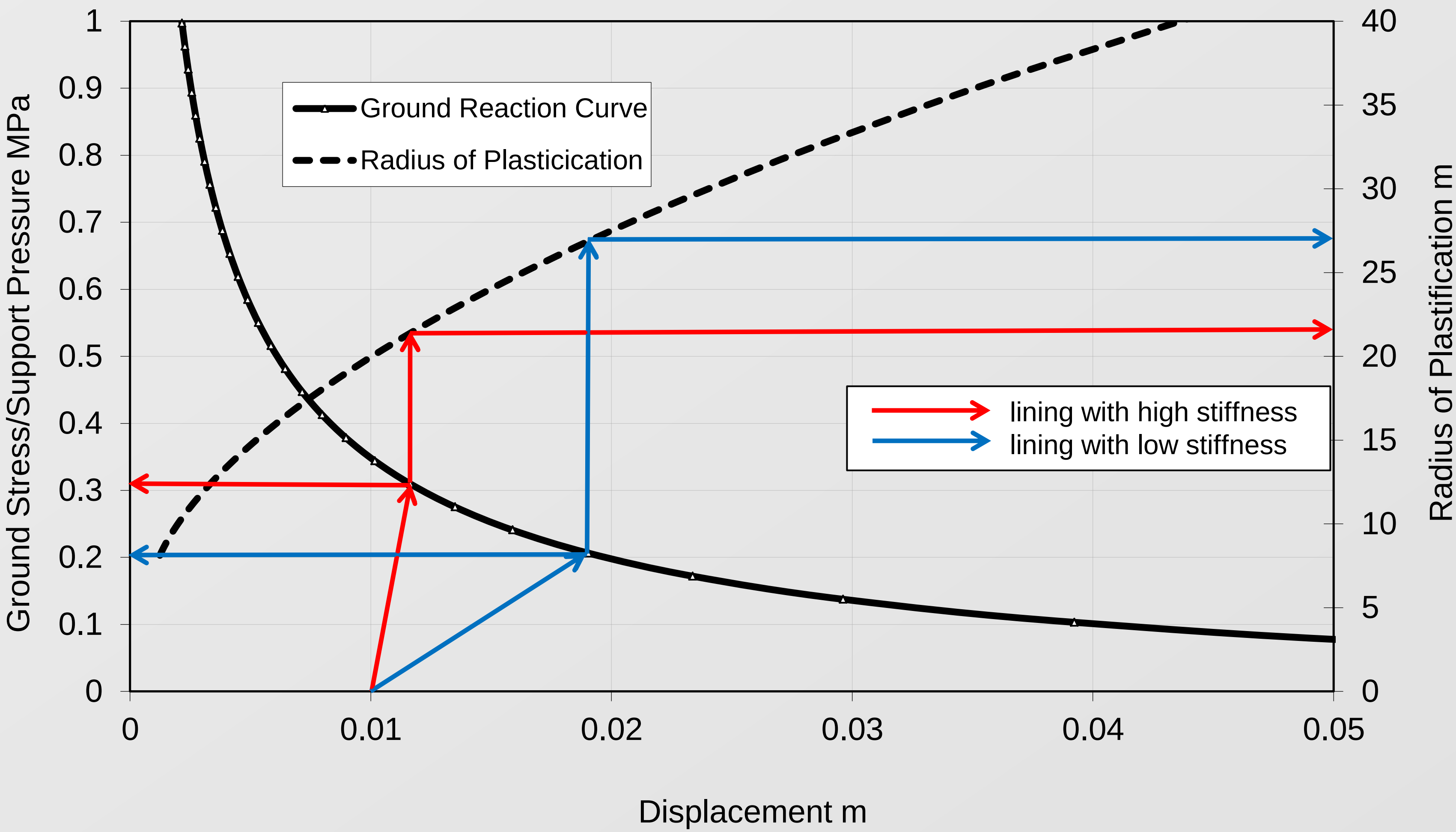
for **ultimate limit state (ULS)** and **serviceability limit state (SLS)**

Structural Design of the Shotcrete Lining

Challenge: **optimize the lining thickness** by **utilizing the load bearing capacity of the surrounding ground**

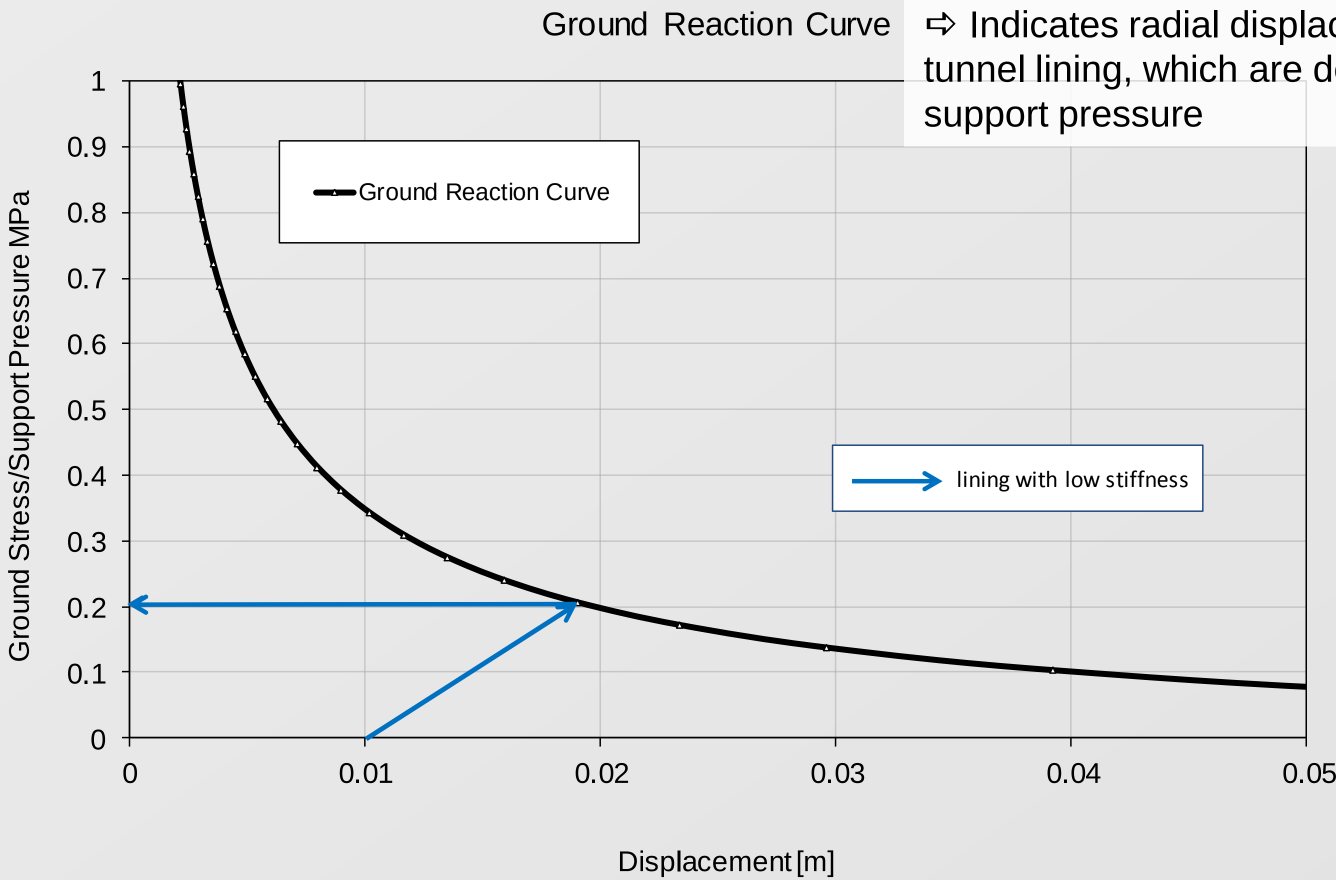
- ❑ **Limitation of deformation and plastification** to an acceptable amount
- ❑ The **stiffer** the **lining** is designed the **more loads** it will attract

Convergence Confinement Diagram



Convergence Confinement Diagram

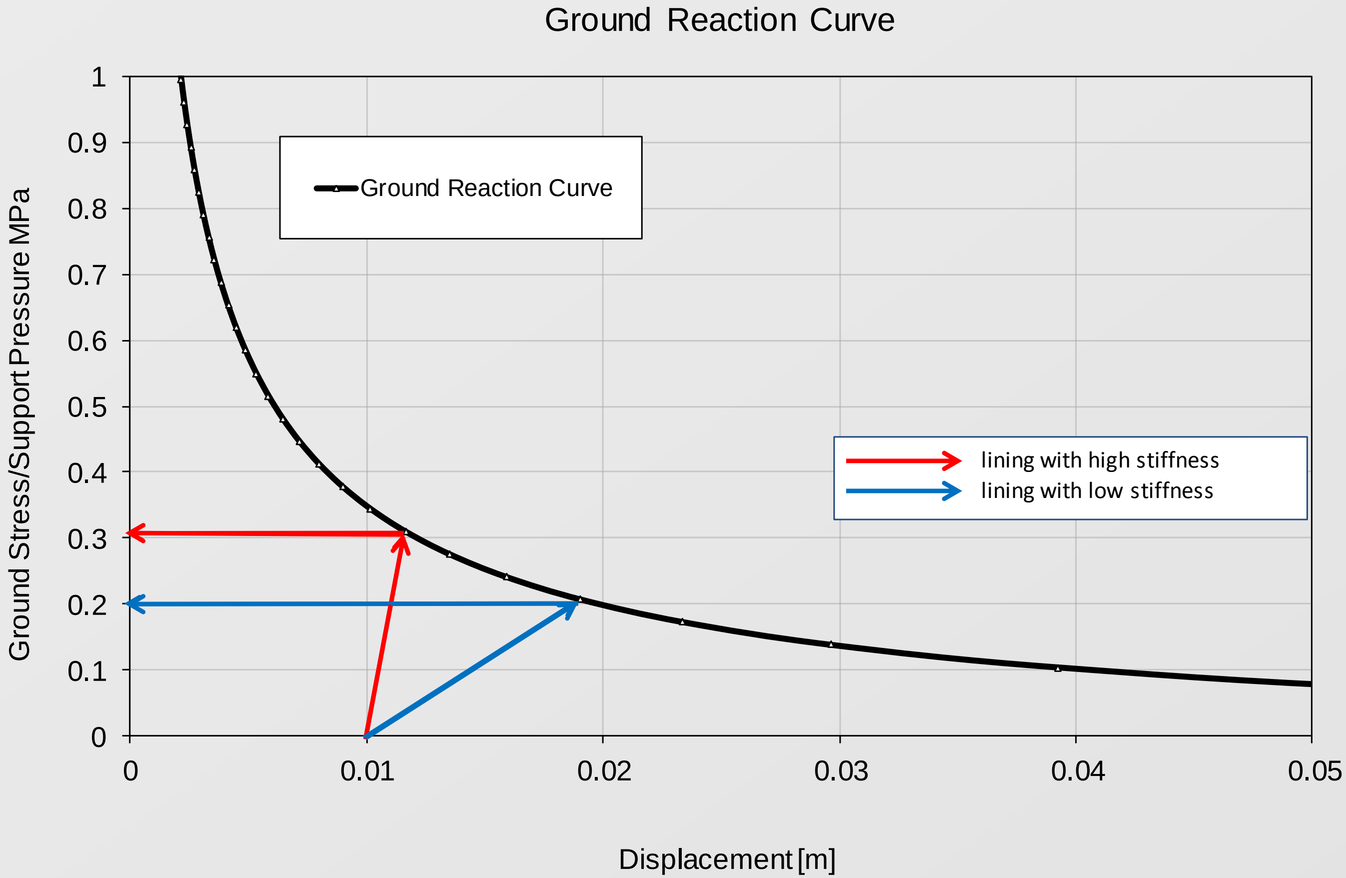
➪ Indicates radial displacements of the tunnel lining, which are depending on the support pressure



blue line shows a lining with low stiffness (thin lining)

▶ **high deformations** but less load on the lining

Convergence Confinement Diagram



red line shows a lining with high stiffness (thick lining)

▶ **lower deformations** resulting in **higher load on the lining** !!

Convergence Confinement Diagram

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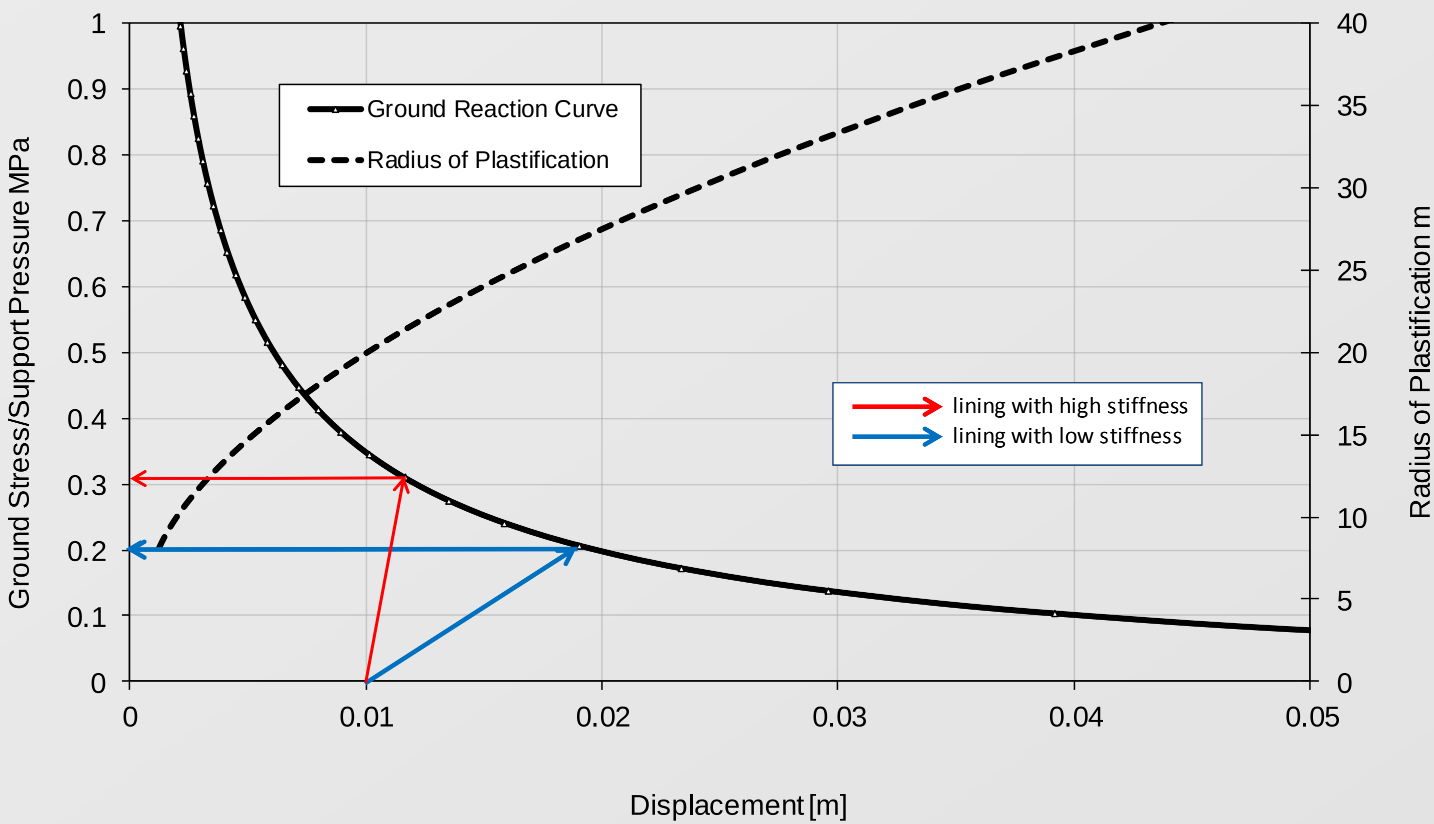
Conclusion:

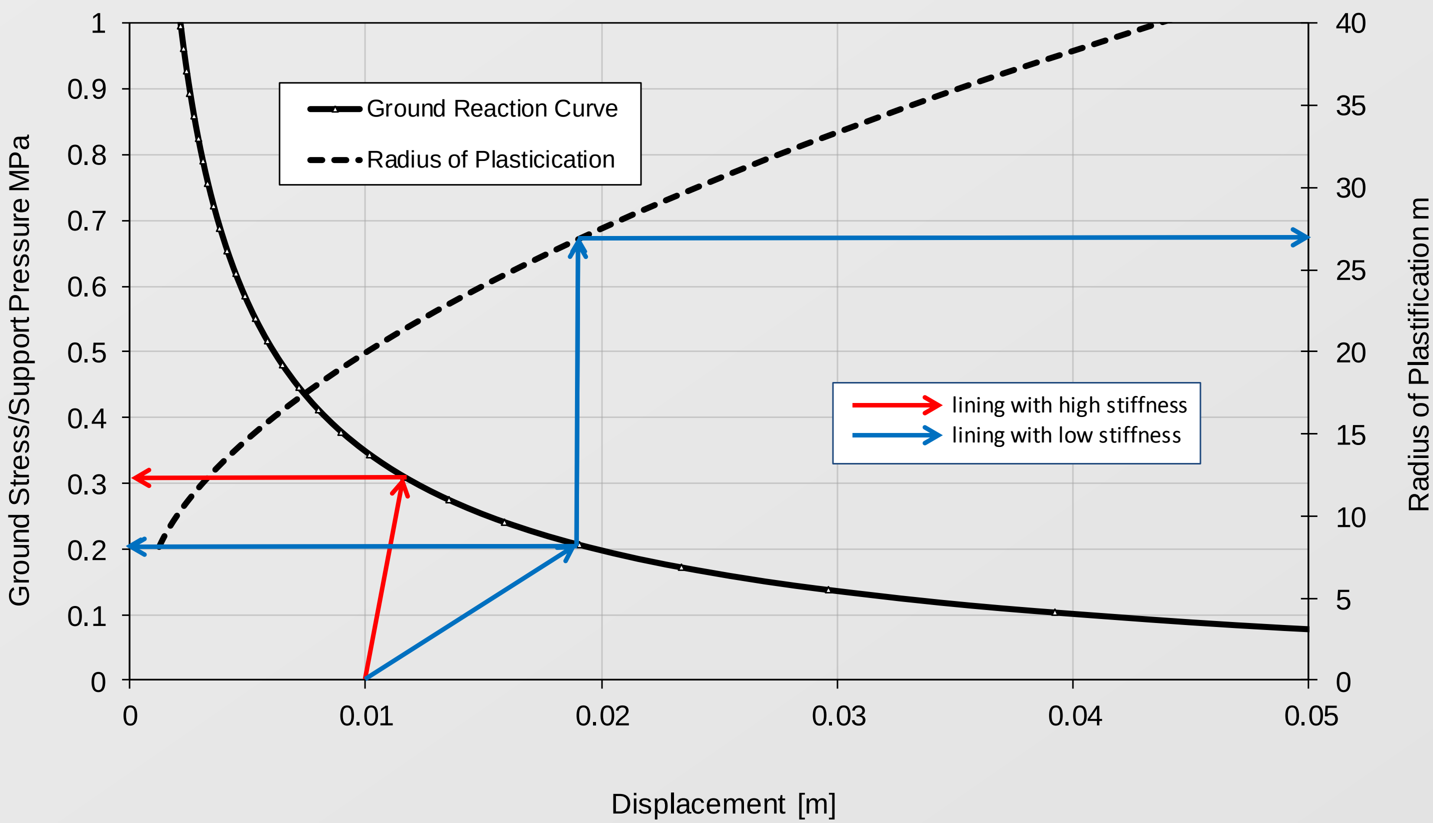
It makes sense to **apply shotcrete in various layers** following individual construction stages rather than applying the whole shotcrete thickness at once !

Convergence Confinement Diagram



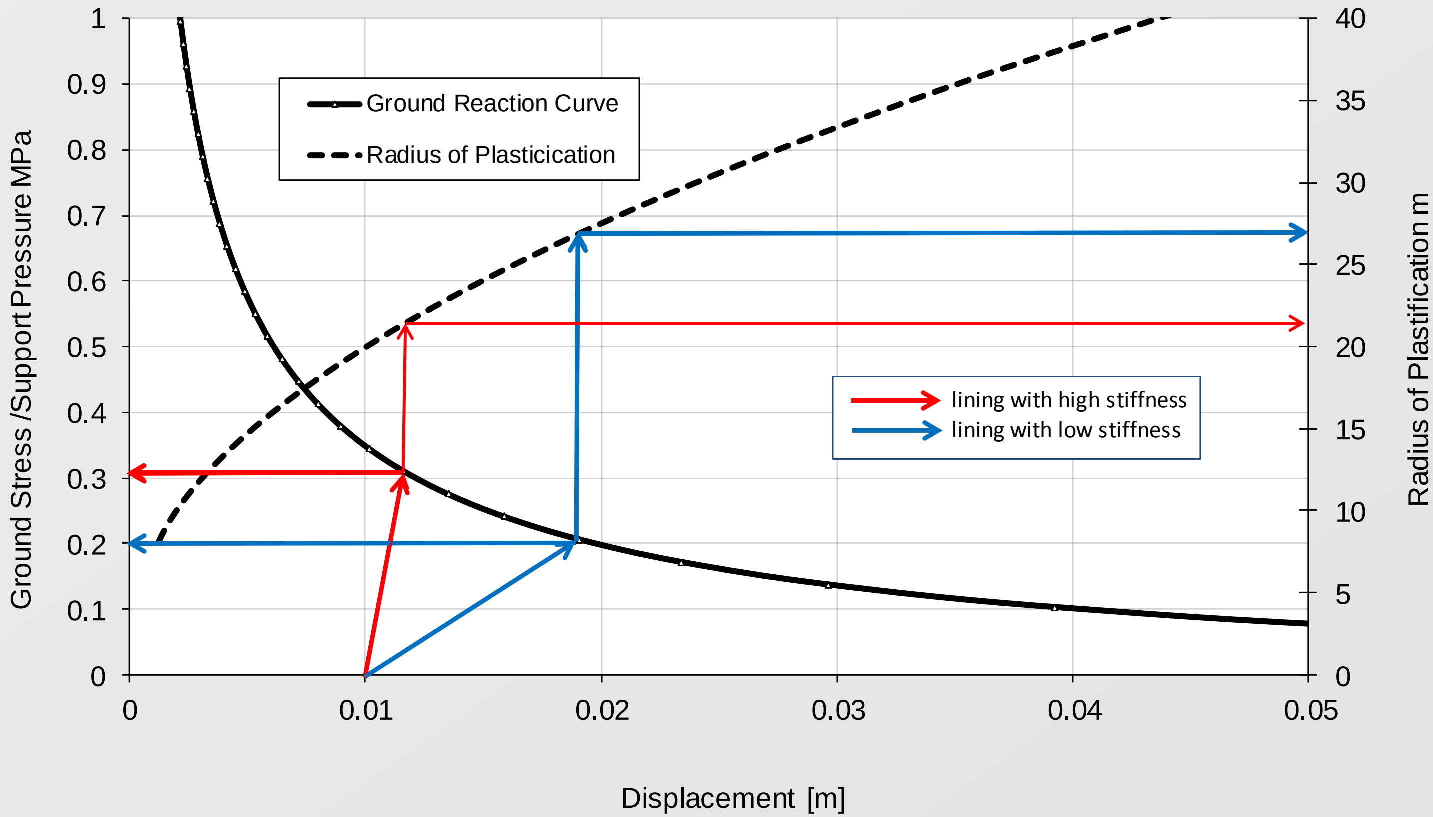
Radius of plastification

Convergence Confinement Diagram



Radius of plastification for **lining with low stiffness**

Convergence Confinement Diagram



Radius of plastification for **lining with high stiffness**

▶ For the **stiff lining** the **radius of plastification is less** than for the lining with low stiffness !!

Reinforcement of existing shotcrete lining

Typical applications for a **second shotcrete** lining:

- **Additional loads** resulting from unexpected ground conditions (additional surface loads, load redistributions etc.)
- A **second, parallel tunnel** is driven while the first tunnel is already in place
- **Cross sections** between two main tunnels need to be installed

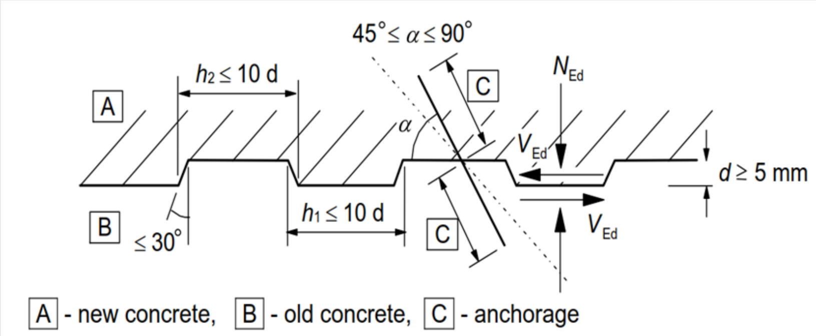
Reinforcement of existing tunnel lining

Strengthening of the shotcrete lining through a second layer, which is added subsequently

Interaction of two shotcrete layers

For structural reasons it is obviously advantageous that both layers act together as one homogeneous cross section (full bond).

▶ bending stiffness is much higher (no slip between layers)



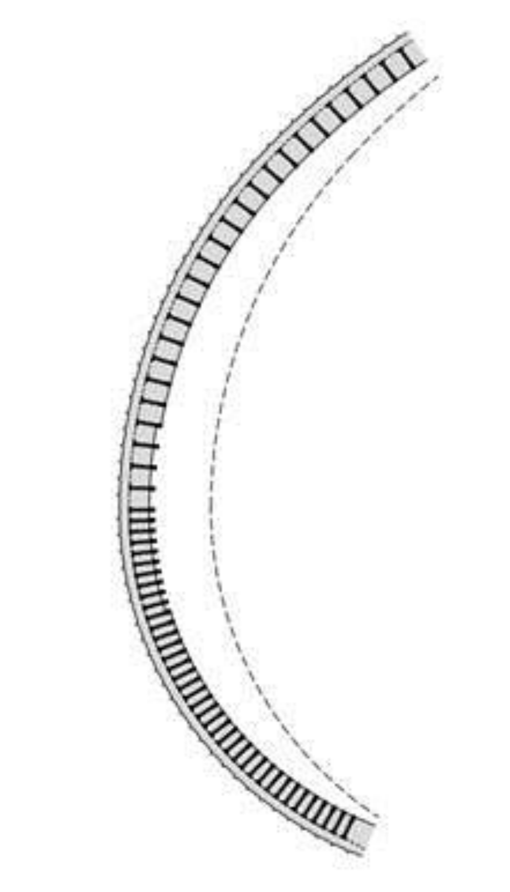
Indented construction joint – EC 2

construction joint e.g. by a high-pressure water jet

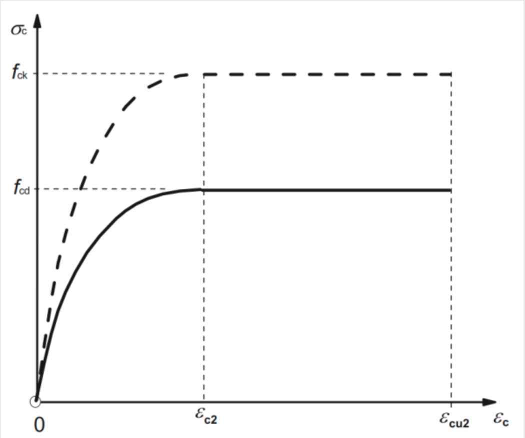
Construction phases and implementation of shear dowels

- It is assumed that a full bond between the shotcrete layers is reached

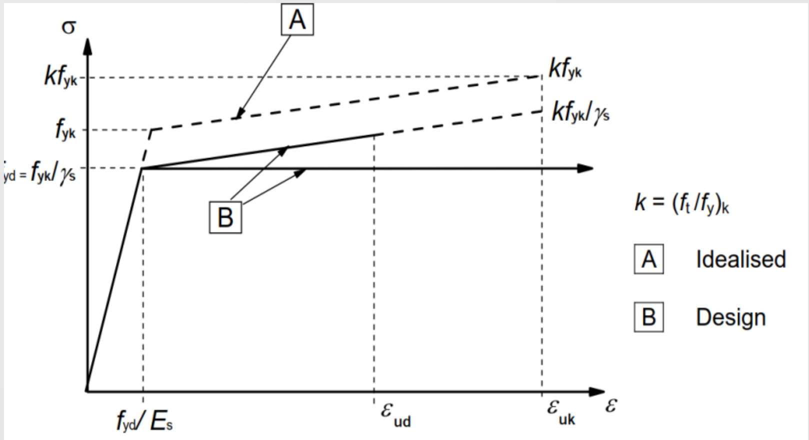
Design and positioning of shear dowels



ULS (Ultimate Limit State) Design for bending with axial force - general assumptions



Parabola – rectangle diagram for **concrete** under compression

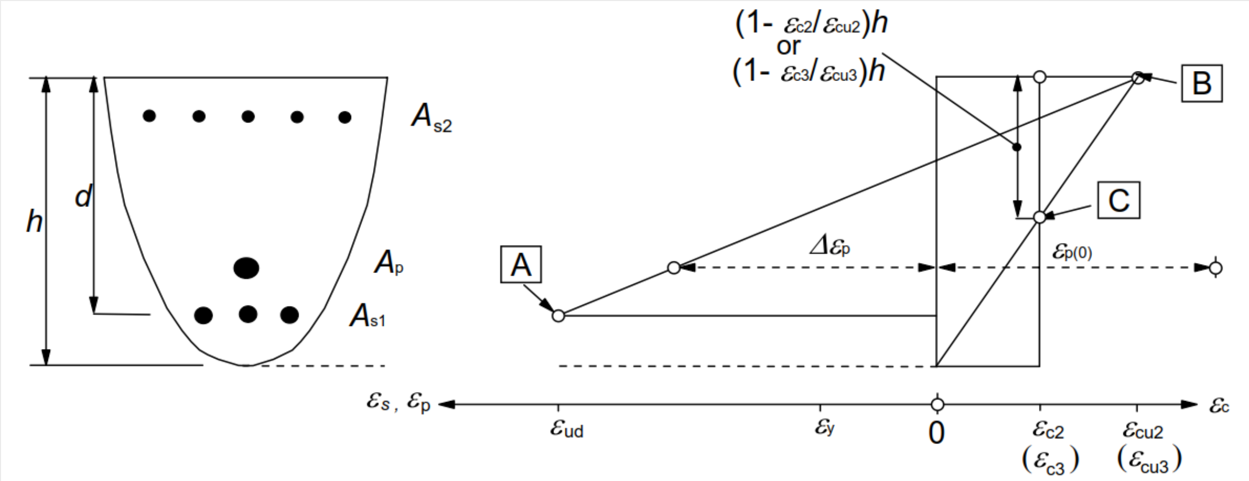


Design stress strain diagram for **reinforcing steel** (tension and compression)

The assumptions for the design are:

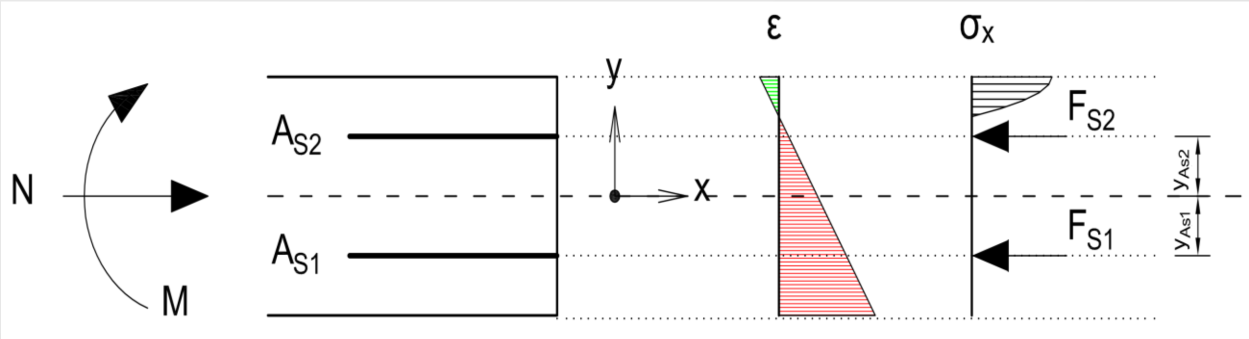
- plane sections remain plane
- the strain in bonded reinforcement, whether in tension or in compression, is the same as that in the surrounding concrete
- the tensile strength of the concrete is ignored
- the stresses in the concrete in compression and in the reinforcing steel are derived from the design stress/strain relationship

Strain/Stress State for design of (Single) Concrete Cross Section



Possible **strain distributions** in the **ultimate limit state** (according to EC 2)

▶ For the **design process** the **strain distribution is varied** (under the boundary conditions as shown) until **a balance between calculated actions and the inner forces** derived from the strain state is **reached**.



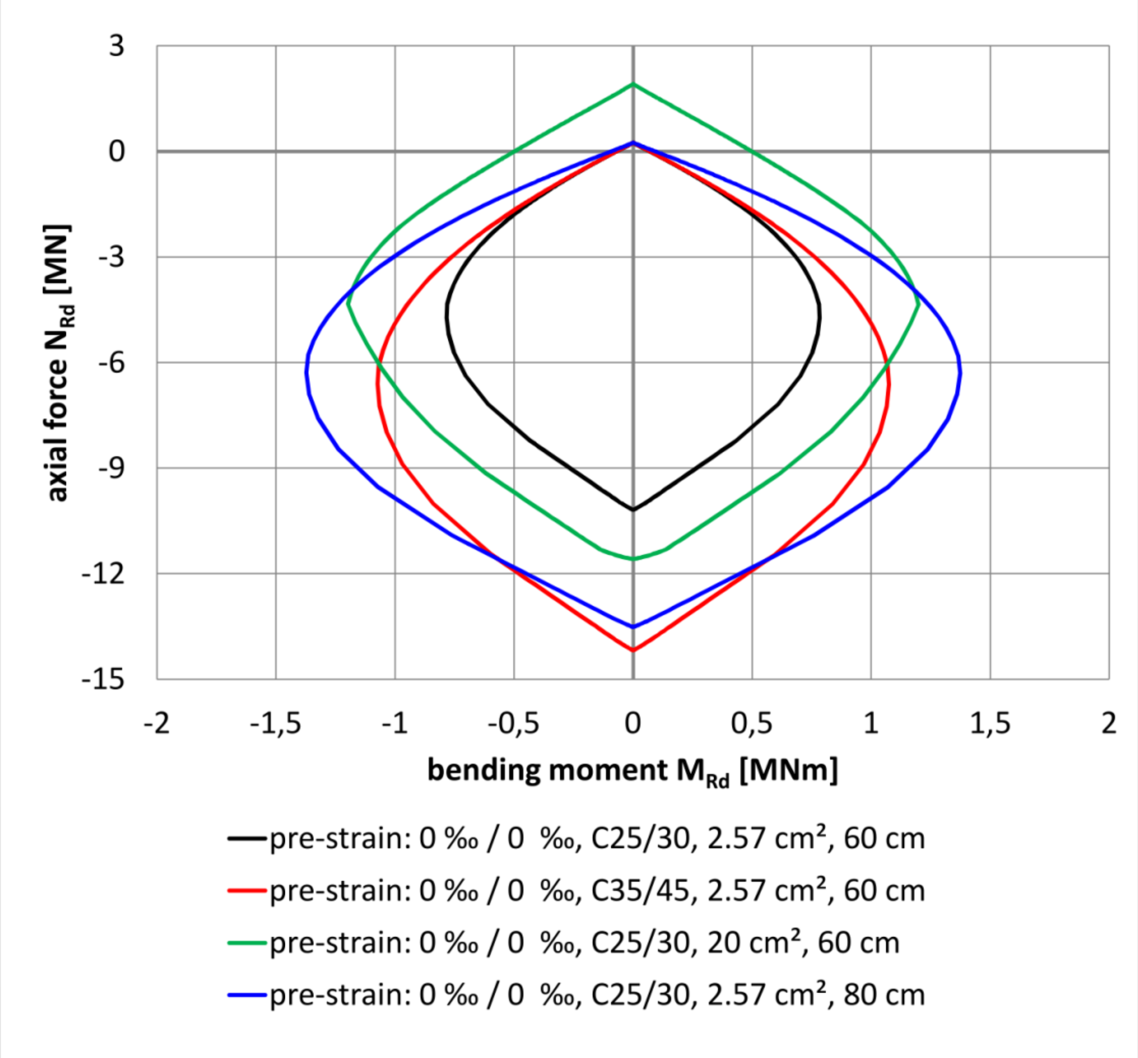
Strain and stress state for design of single concrete cross section

$$\Sigma H = 0$$

$$\Sigma M = 0$$

Bending moment – axial force interaction diagram

(M-N interaction diagram –single layer concrete cross section)



M-N combinations for **allowable** and unallowable (limit strain exceeded) **strain states**

Two layer shotcrete design

Challenge:

A part of the cross section, the **first shotcrete layer**, is **already loaded** while the newly applied shotcrete, the **second layer, is stress free !!**

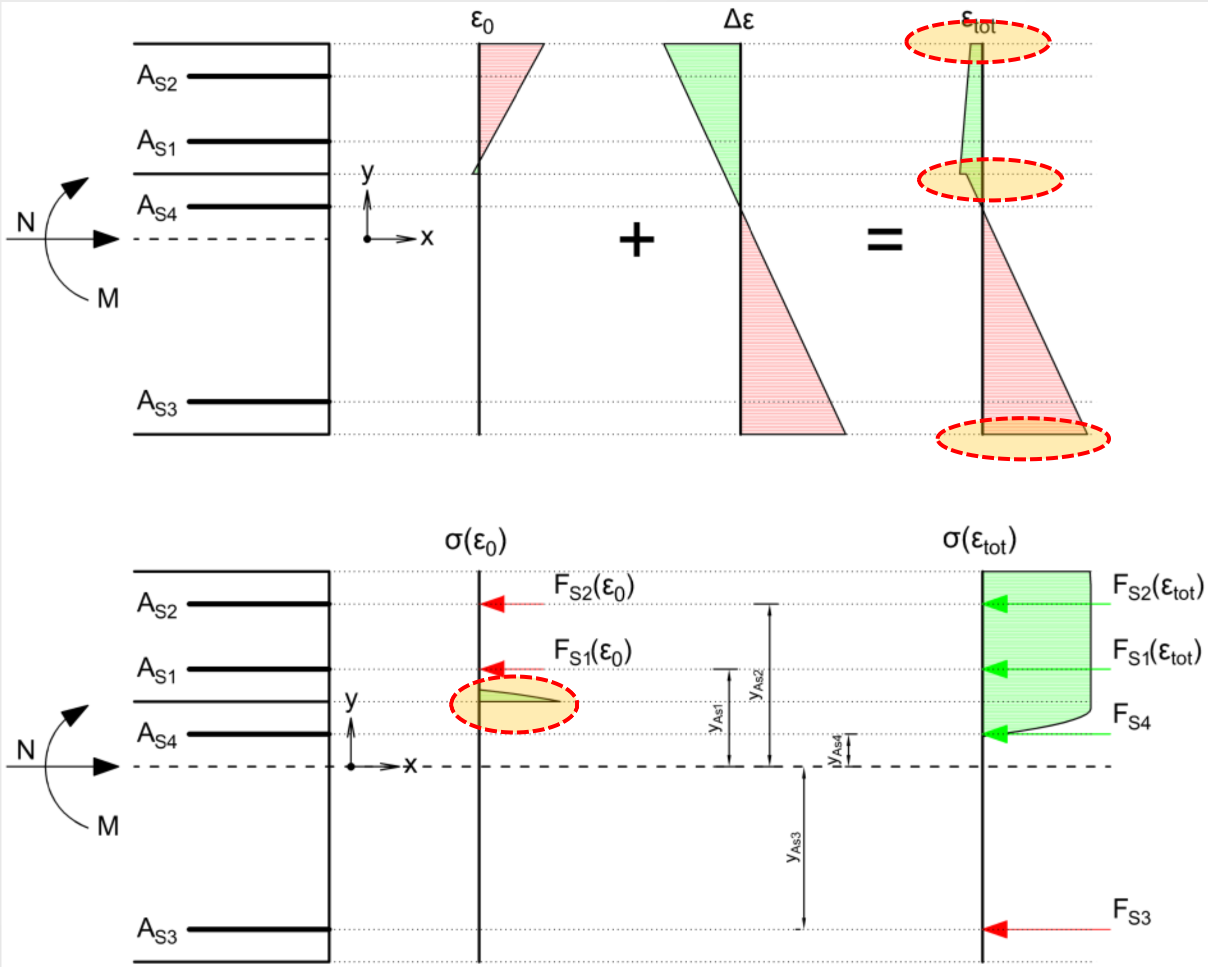
Two layer shotcrete design

▶ Procedure to determine the **additional capacity** of the whole cross section:

1. apply **additional strain ($\Delta\varepsilon$)** to the **whole cross section** (consisting of 2 layers)
   - Additional strain ($\Delta\varepsilon$) is added to existing strain (ε_0)
   - assumption: plane sections remain plane

2. **strain distribution is varied** until the **limit strains** according to EC 2 are reached in
   - **top** fibre
   - **bottom** fibre
   - <u>**Interface**</u> fibre (between first and second layer)

Two layer shotcrete design



top fibre

interface fibre

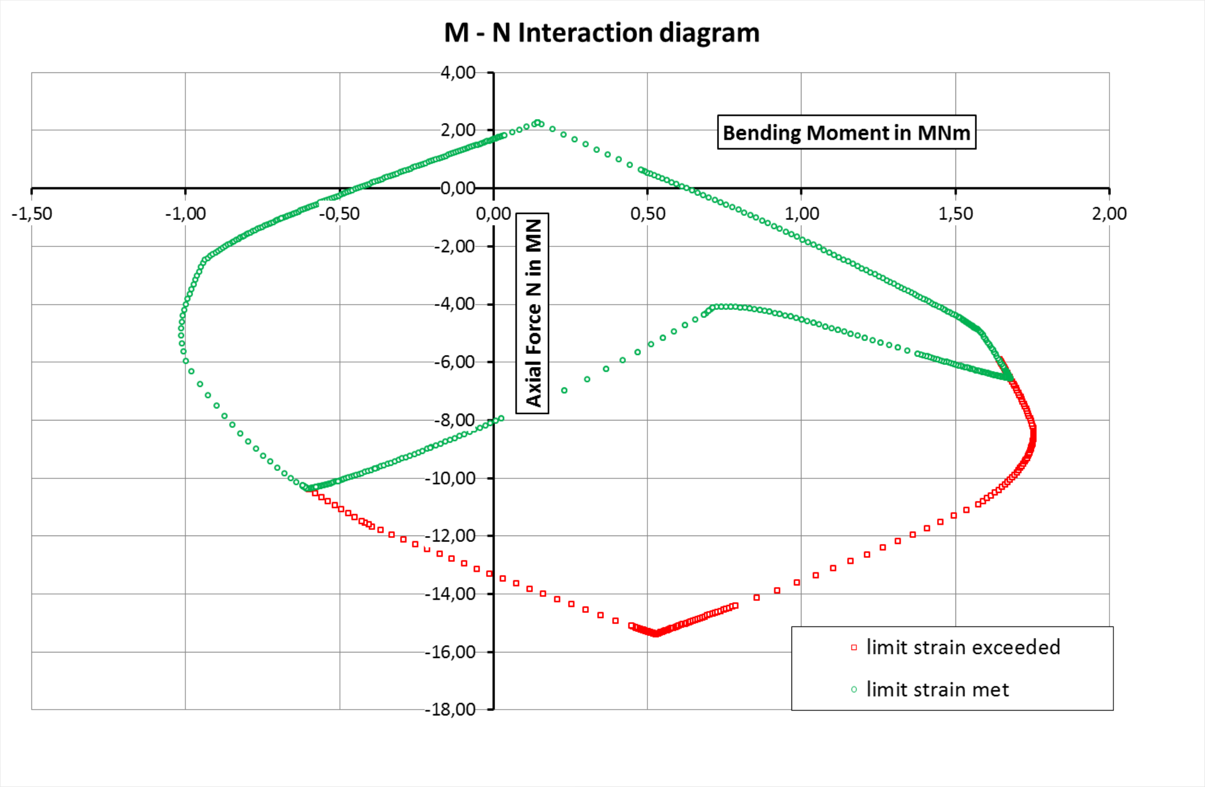
bottom fibre

$$\Sigma H = 0$$

$$\Sigma M = 0$$

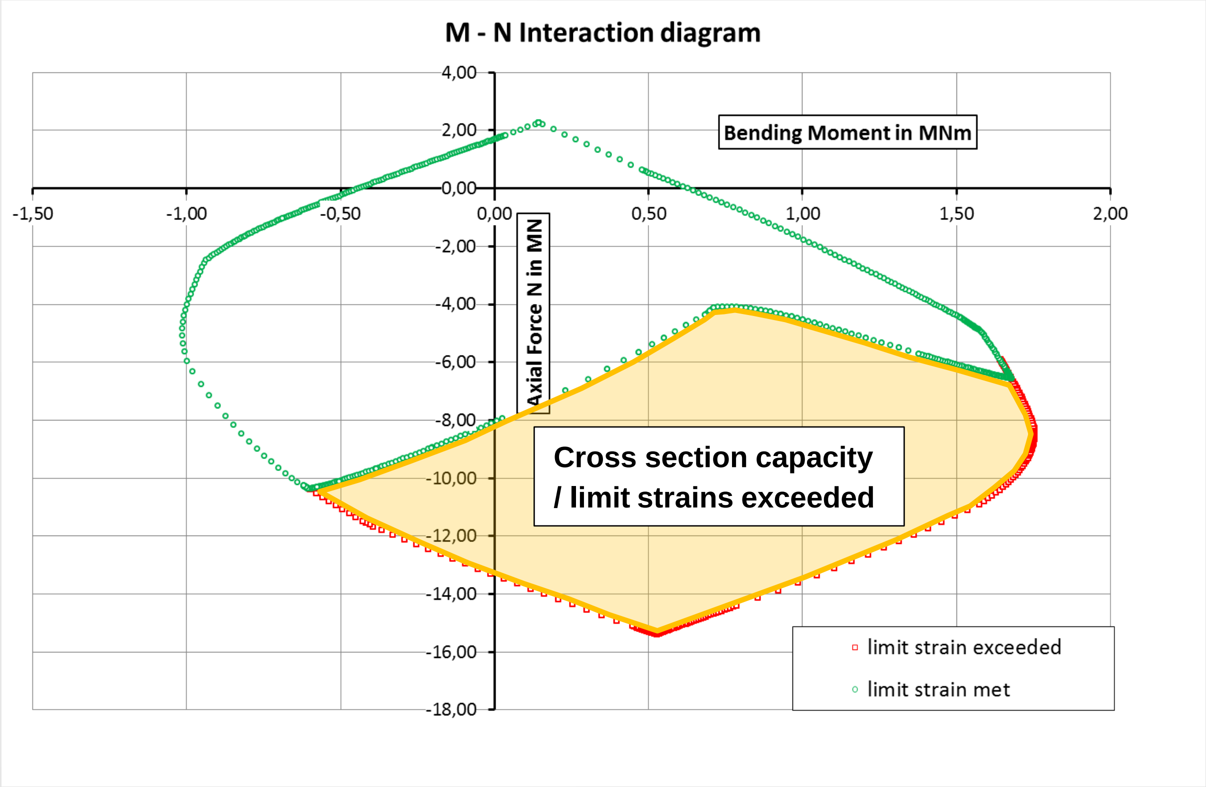
Strain and stress state for design of **composite concrete cross section**

Bending moment – axial force interaction diagram
(M-N interaction diagram)



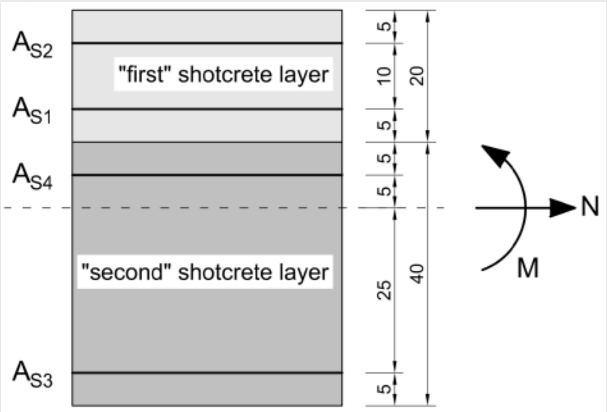
▶ **Additional capacity** of the composite concrete cross section is **no more symmetric !!**

Bending moment – axial force interaction diagram (M-N interaction diagram)



▶ **Additional capacity** of the composite concrete cross section is **no more symmetric !!**

Discussion of specific results – base case



Base case of composite cross section and definition of positive sectional forces

Shotcrete layer	Concrete strength	Reinforcement strength	Reinforcement area
First shotcrete layer	C25/30 f_{ck} = 25 MPa α_{cc} = 1.0 γ_c = 1.5	B550 f_{yk} = 550 MPa γ_s = 1.15	A_{S1} = 2,57 cm^2/m A_{S2} = 2,57 cm^2/m
Second shotcrete layer			A_{S3} = 2,57 cm^2/m A_{S4} = 2,57 cm^2/m

Input data for base case

Discussion of specific results – base case

Three pre-strain states of the first shotcrete layer are investigated:

Case 1: **low** utilization of the initial cross section

Case 2: **moderate** utilization of the initial cross section

Case 3: **maximum** utilization of the initial cross section

Discussion of specific results – base case

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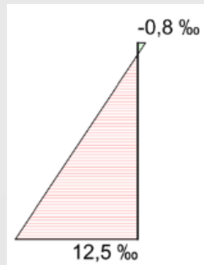
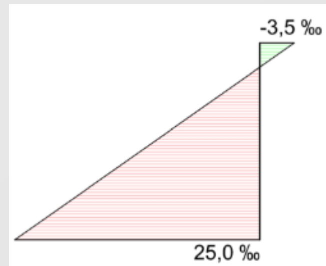
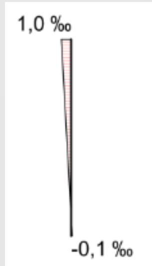
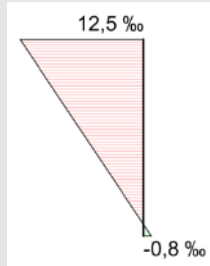
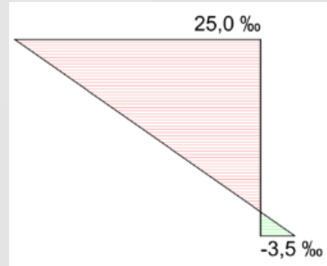
Case	**1a**	**2a**	**3a**
ε_{top} [‰]	-0,1	-0,8	-3,5
ε_{bottom} [‰]	1,0	12,5	25
pre-strain distribution			

Case	**1b**	**2b**	**3b**
ε_{top} [‰]	1,0	12,5	25
ε_{bottom} [‰]	-0,1	-0,8	-3,5
pre-strain distribution			

Cases of **pre-strain conditions** of **first** shotcrete layer

Discussion of specific results – base case

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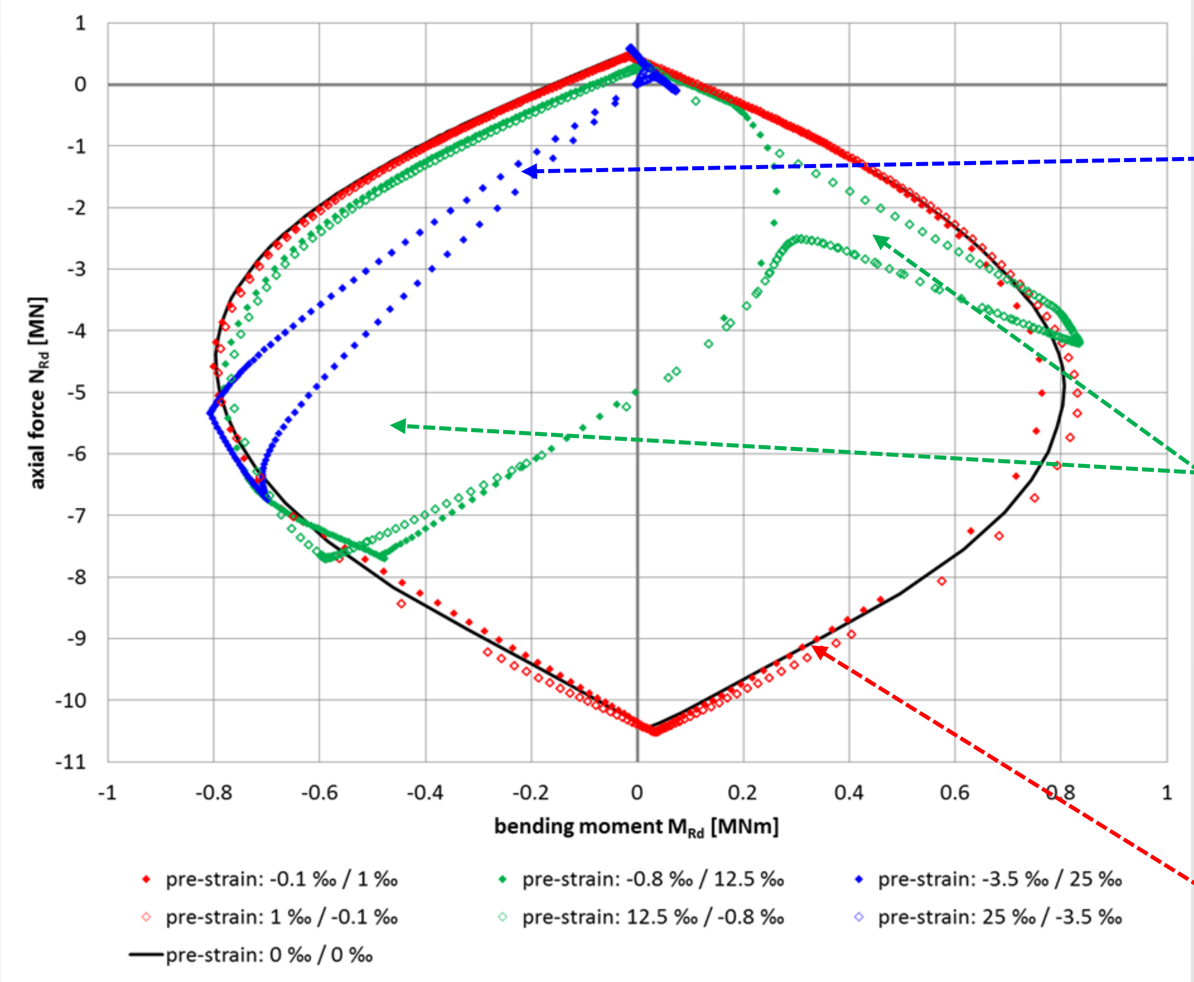


General case – M-N interaction diagrams

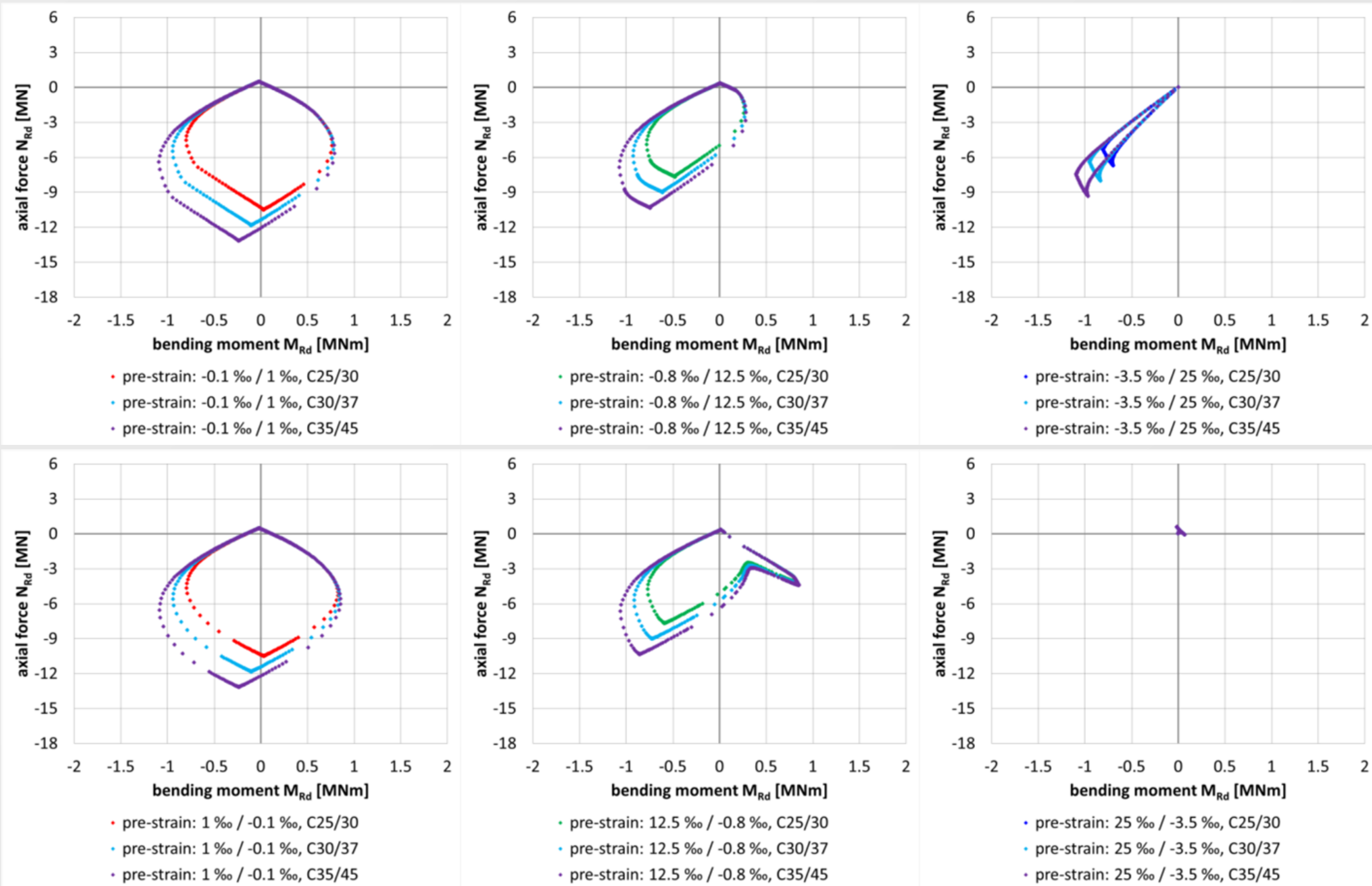
In case of **maximum utilization** only very specific M-N combinations (within the blue area) can be applied
⇨ **design approach with very high utilization of the first shotcrete layer is not recommended !**

moderate utilization:
Higher additional capacity for **cases with negative bending moment** for the combined cross section.

The **higher** the **utilization of the first shotcrete layer**, the **lower the additional load bearing capacity of the combined cross section !!**

For **low utilization**, the interaction diagram is very similar to the base case without any pre strain.

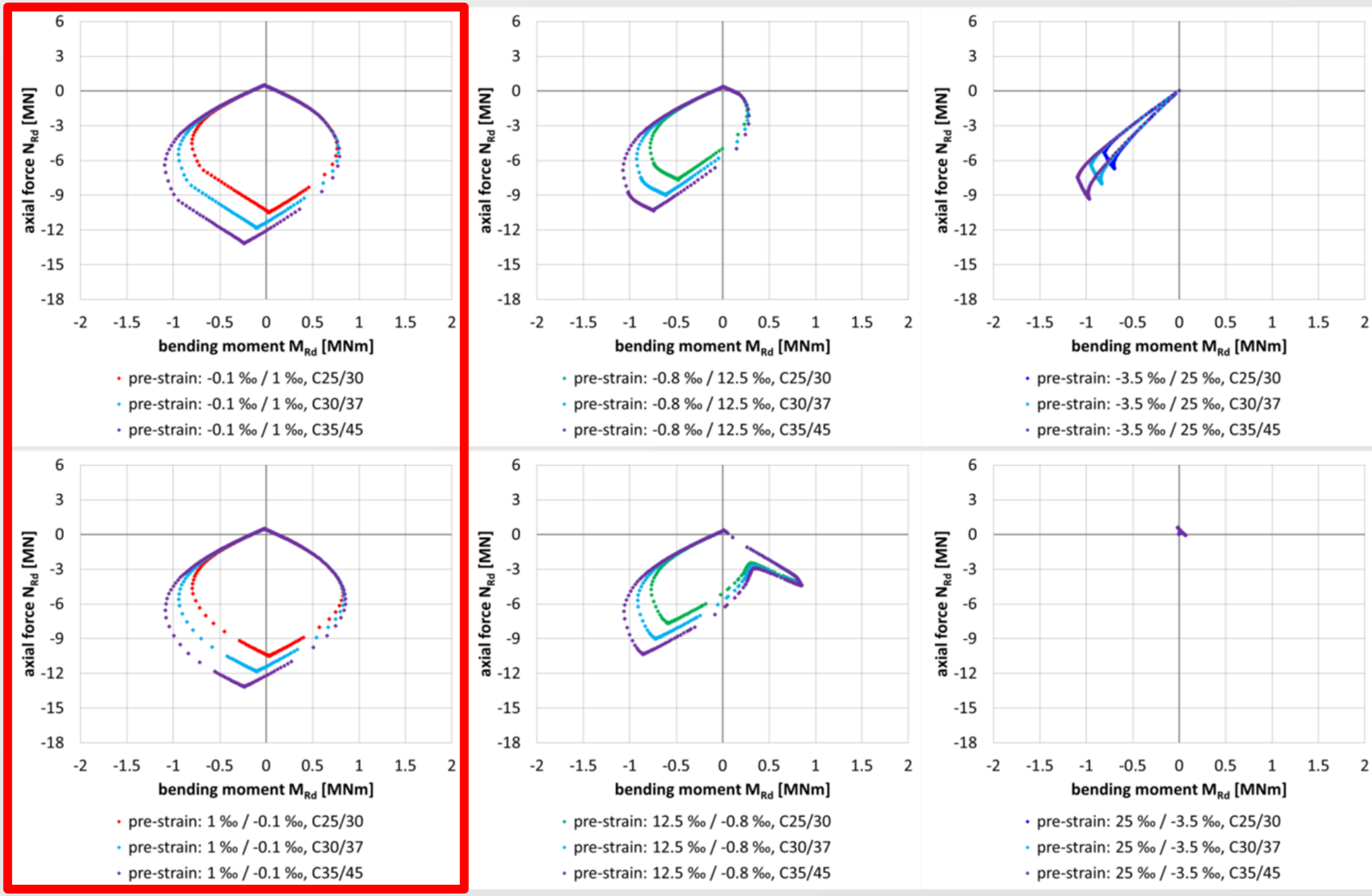
Discussion of specific results – influence of **concrete strength**



M-N interaction diagrams – influence of the concrete strength

Discussion of specific results – influence of **concrete strength**

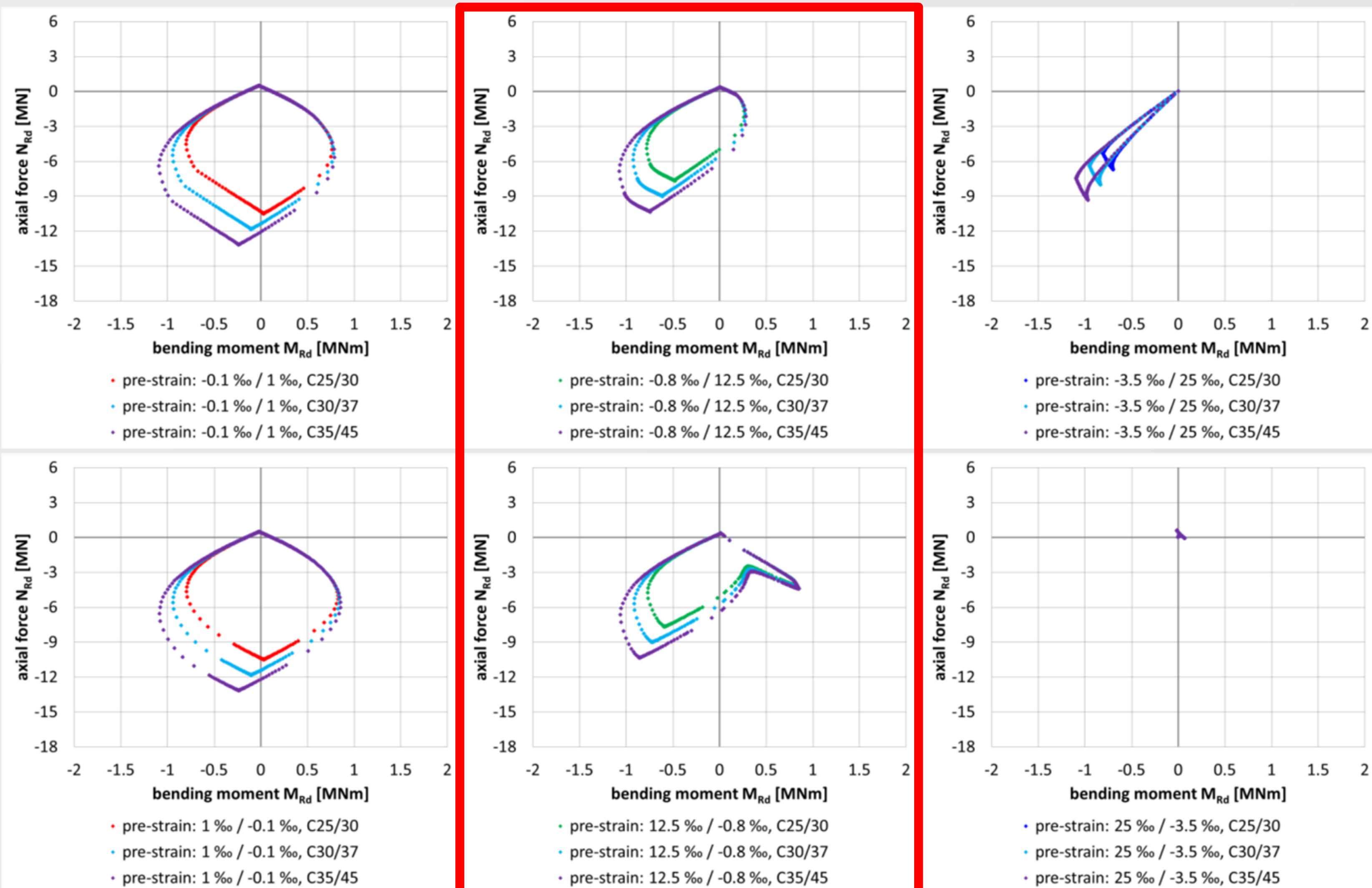
Low utilization initial cross section



M-N interaction diagrams – influence of the concrete strength

Discussion of specific results – influence of **concrete strength**

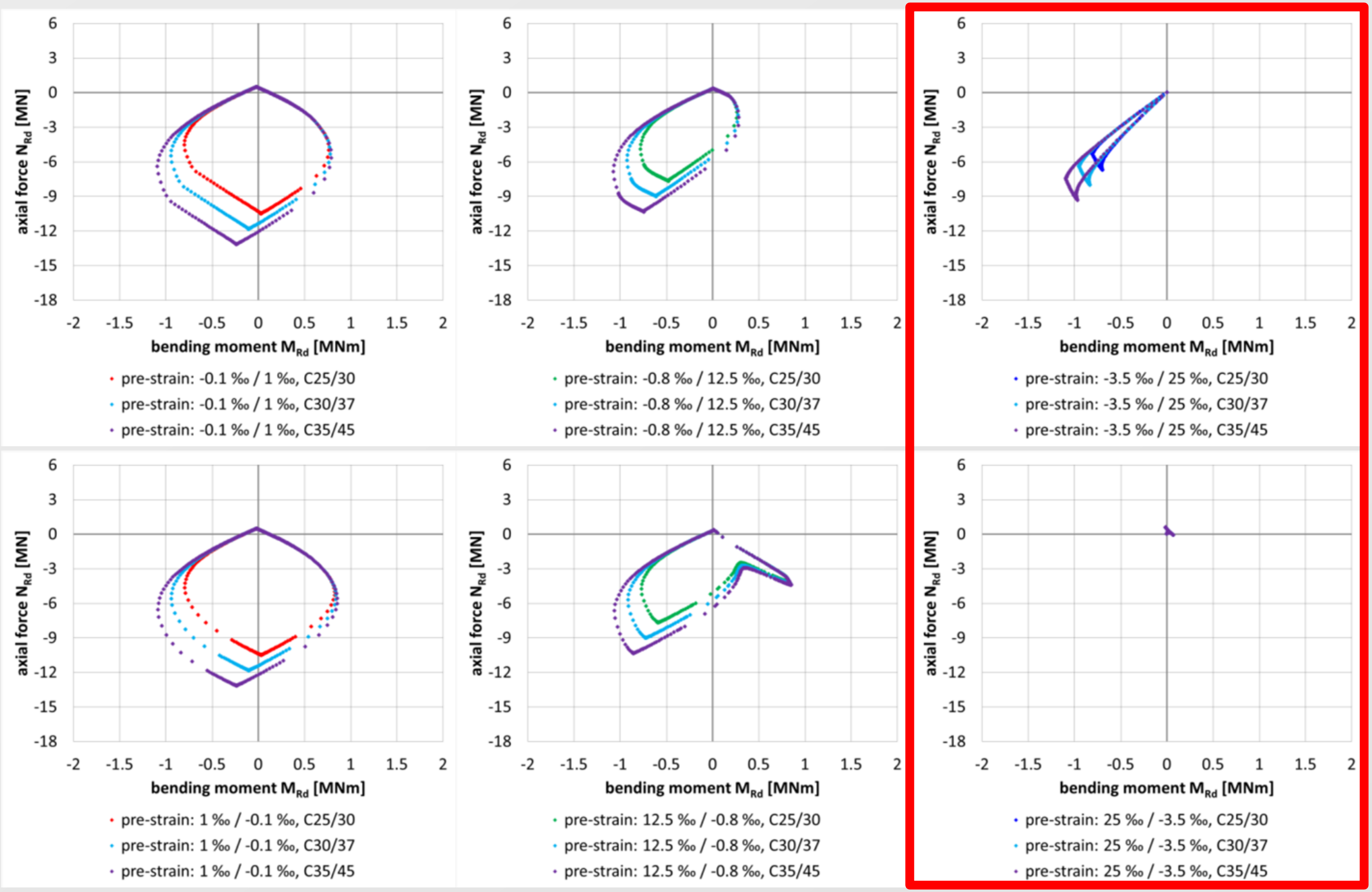
Medium utilization initial cross sec.



M-N interaction diagrams – influence of the concrete strength

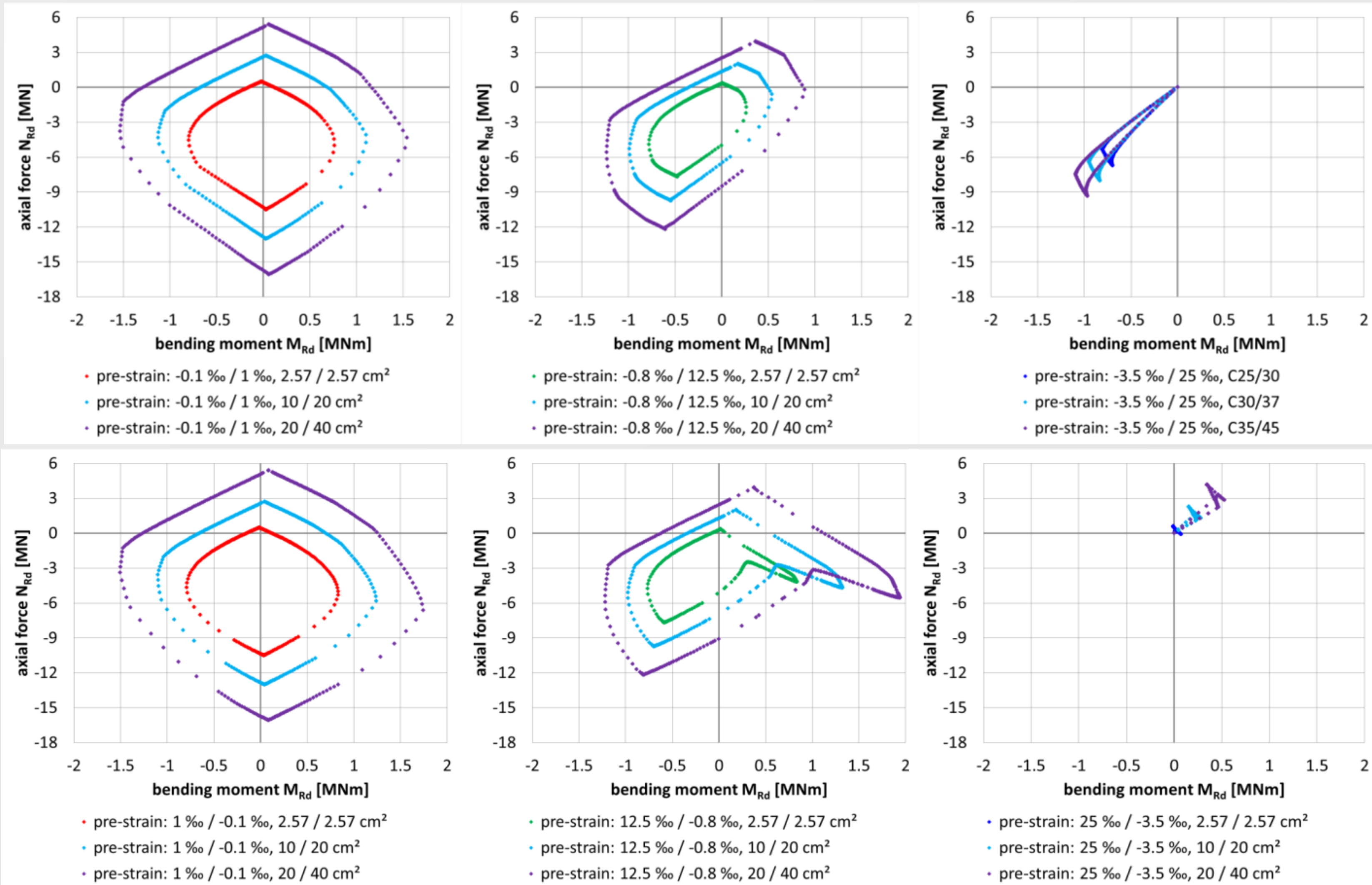
Discussion of specific results – influence of **concrete strength**

High utilization initial cross section



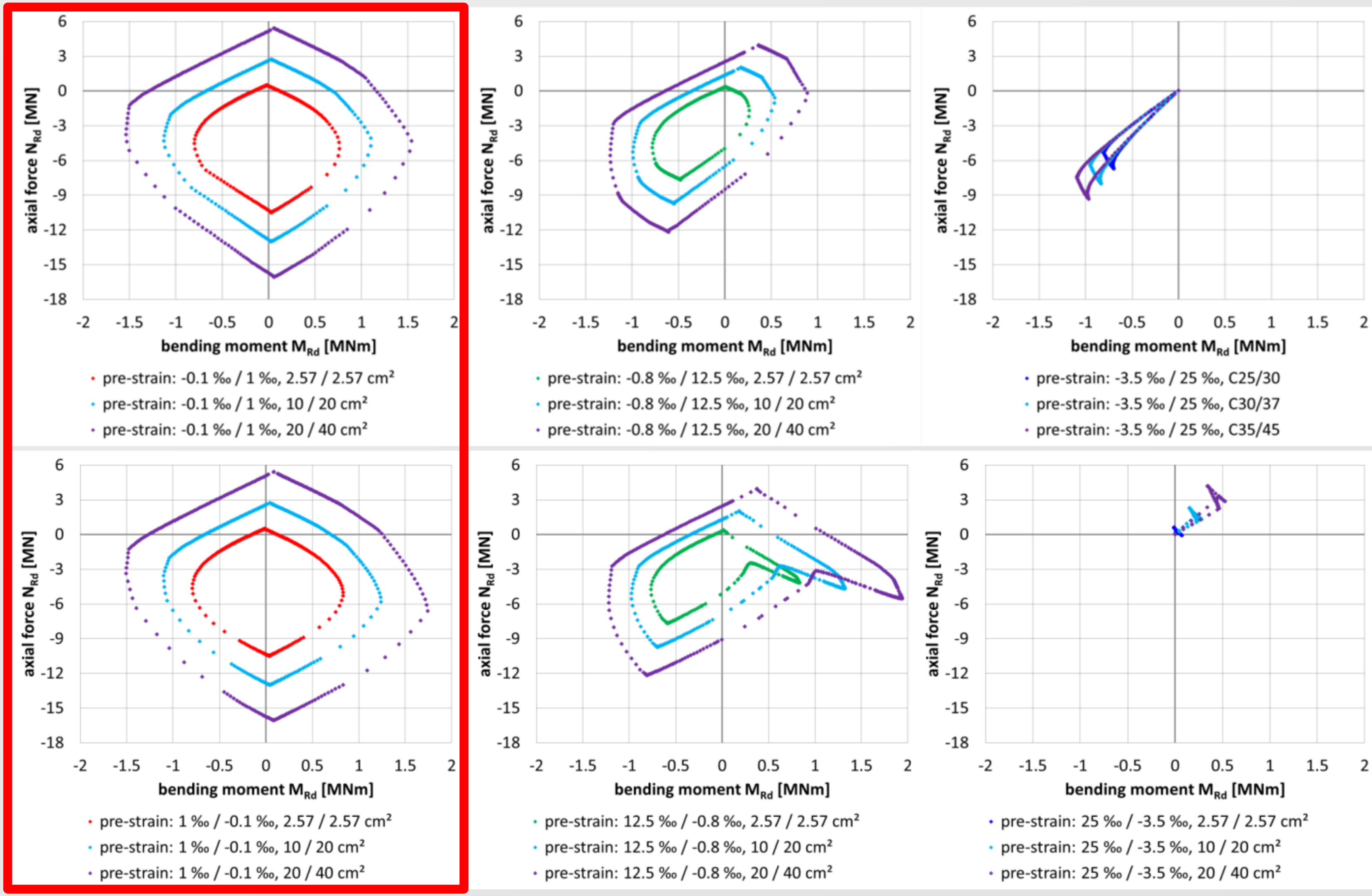
M-N interaction diagrams – influence of the concrete strength

Discussion of specific results – influence of **reinforcement amount**



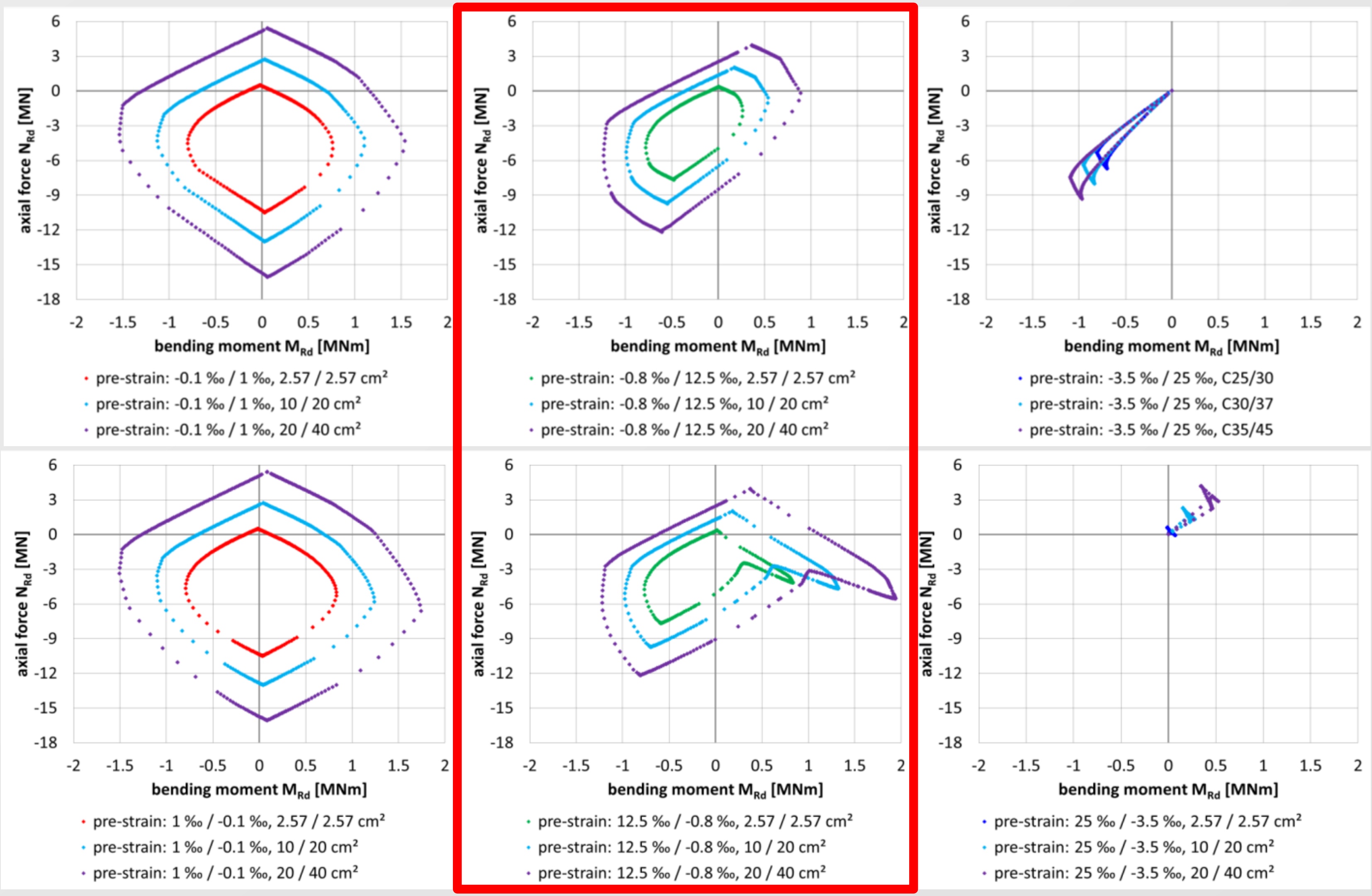
M-N interaction diagrams – influence of reinforcement amount

Discussion of specific results – influence of **reinforcement amount**



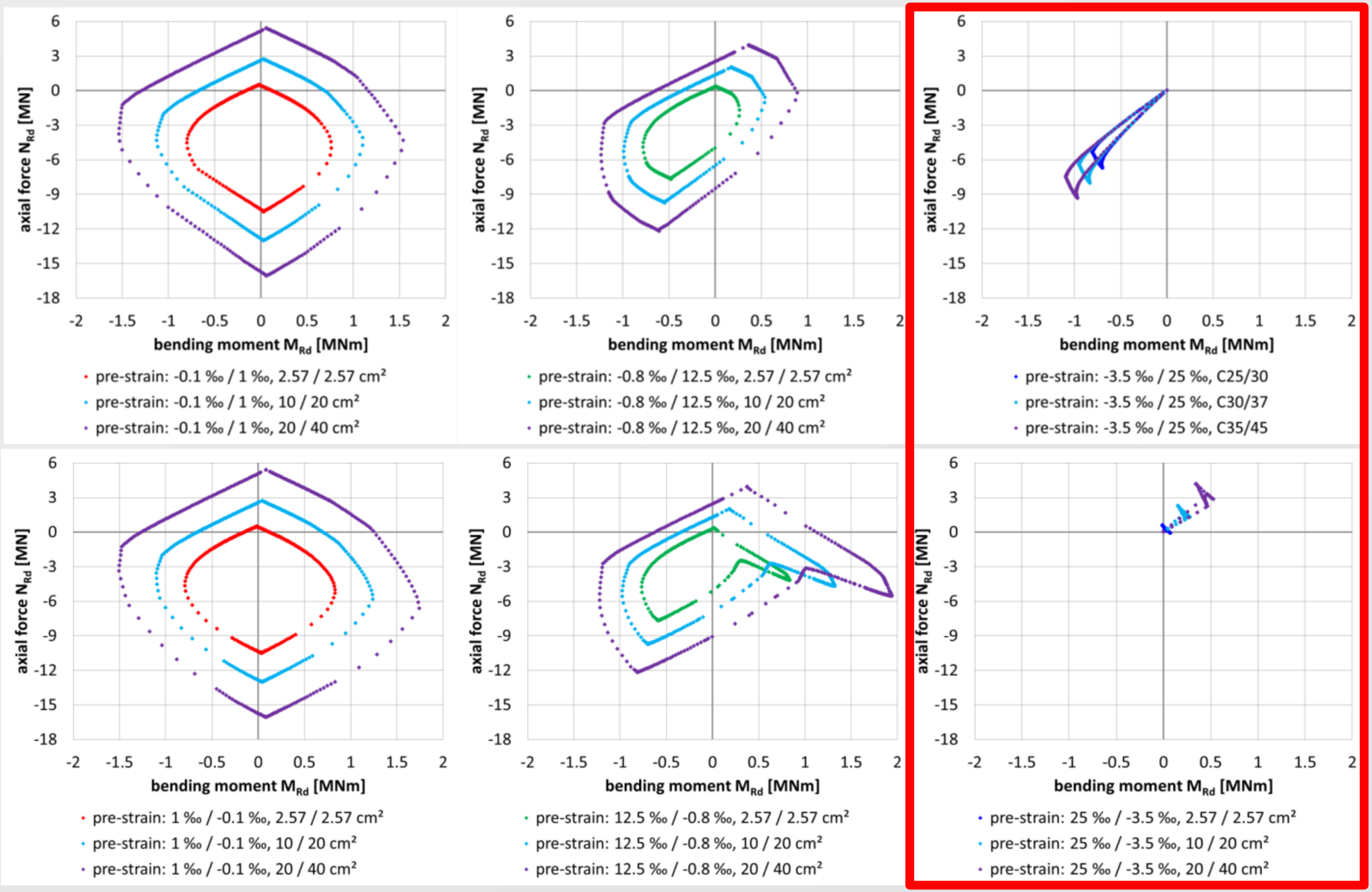
M-N interaction diagrams – influence of reinforcement amount

Discussion of specific results – influence of **reinforcement amount**



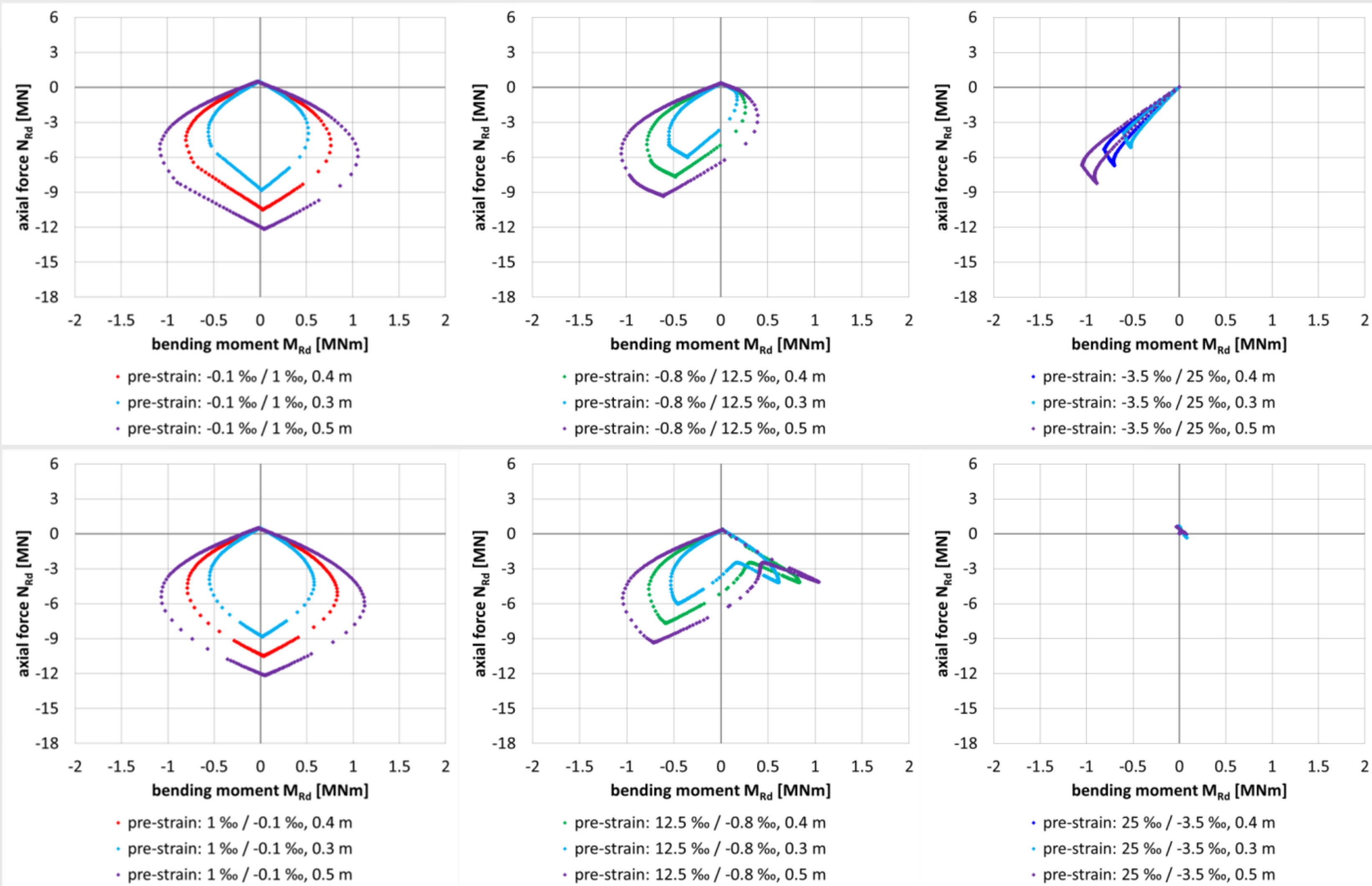
M-N interaction diagrams – influence of reinforcement amount

Discussion of specific results – influence of **reinforcement amount**



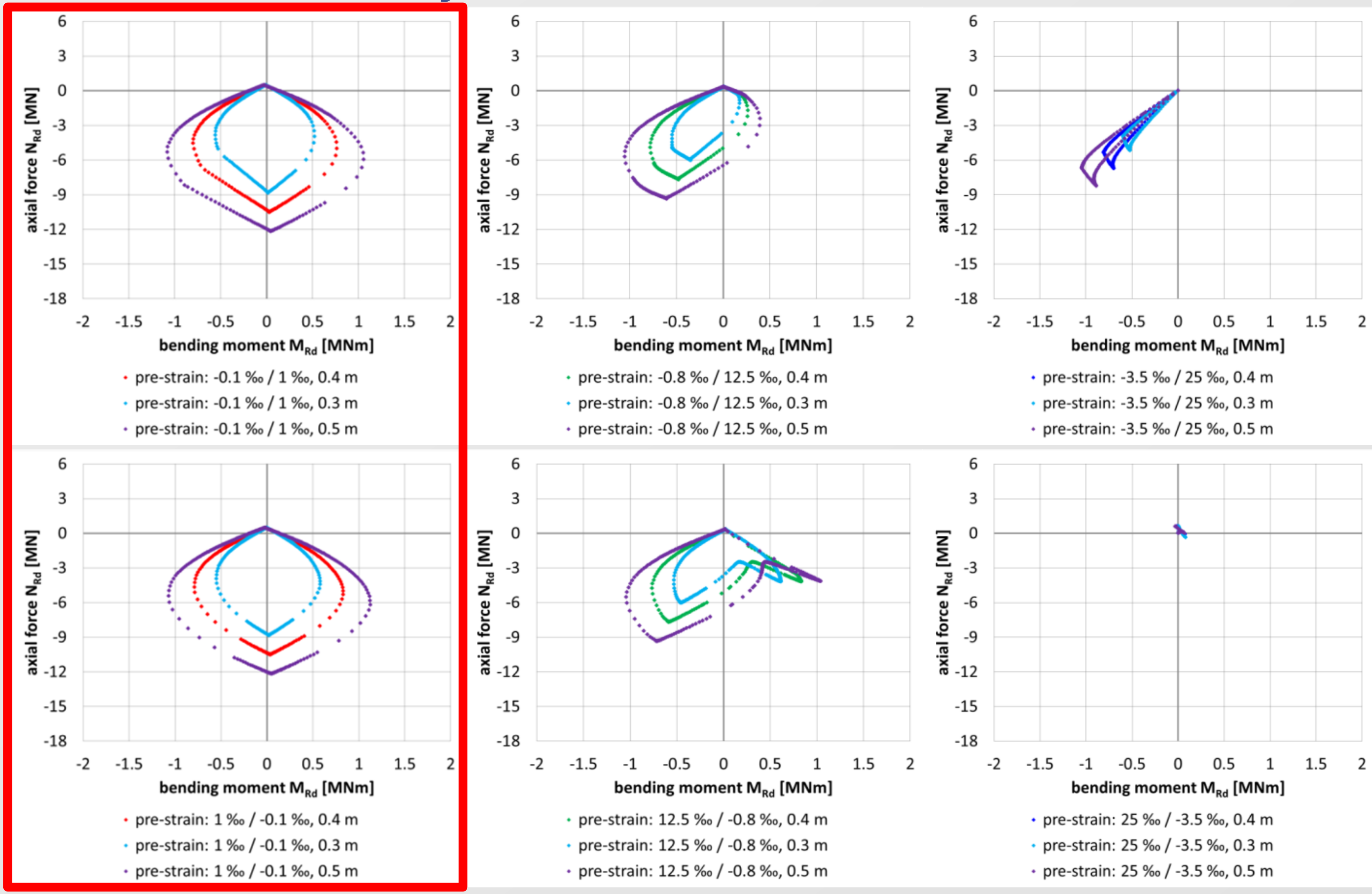
M-N interaction diagrams – influence of reinforcement amount

Discussion of specific results – influence of **thickness** of the **second shotcrete layer**



M-N interaction diagrams – influence of the thickness of the second shotcrete layer

Discussion of specific results – influence of **thickness** of the **second shotcrete layer**



M-N interaction diagrams – influence of the thickness of the second shotcrete layer

Discussion of specific results – influence of **thickness** of the **second shotcrete layer**

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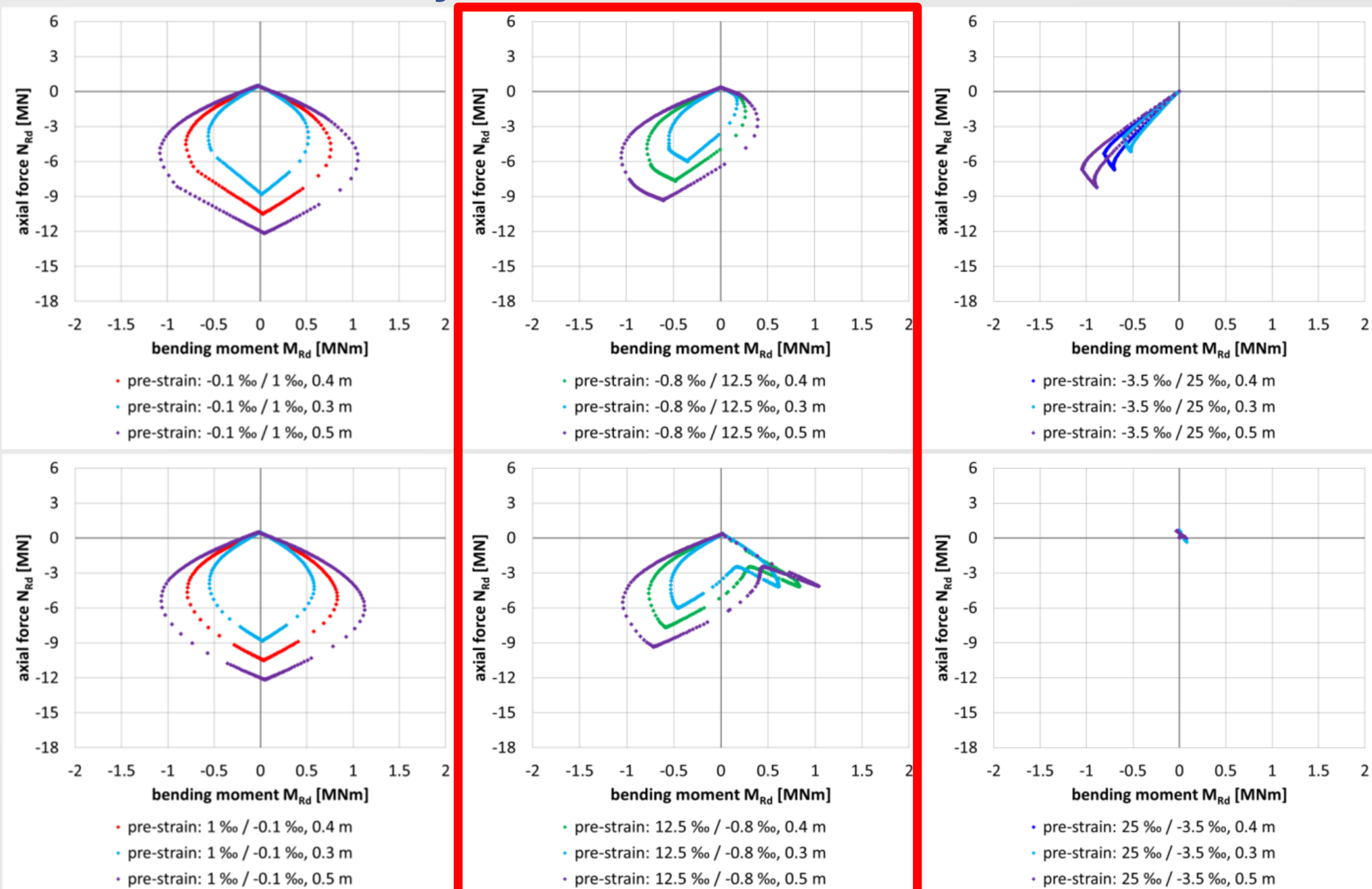
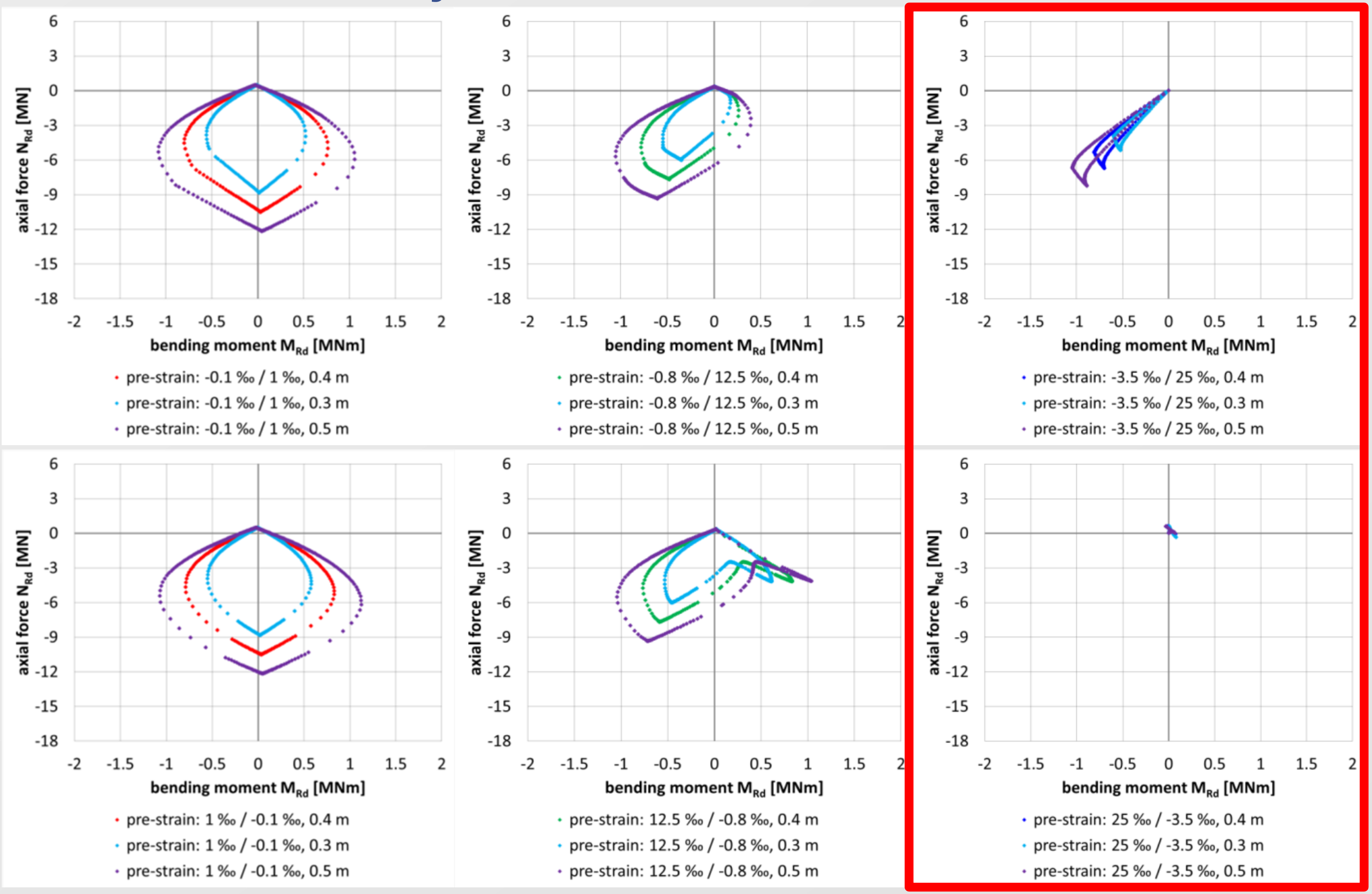


M-N interaction diagrams – influence of the thickness of the second shotcrete layer

Discussion of specific results – influence of **thickness** of the **second shotcrete layer**



M-N interaction diagrams – influence of the thickness of the second shotcrete layer

Conclusion

- **Pre-strain is to be considered**
- **No fibre shall exceed limit strain** as per EC2
- **First shotcrete layer** shall **not be at limit state** of strain
- **General Interaction diagrams can NOT be provided** due to unlimited number of pre strain combinations
- **Design** only possible **by applying specific software**

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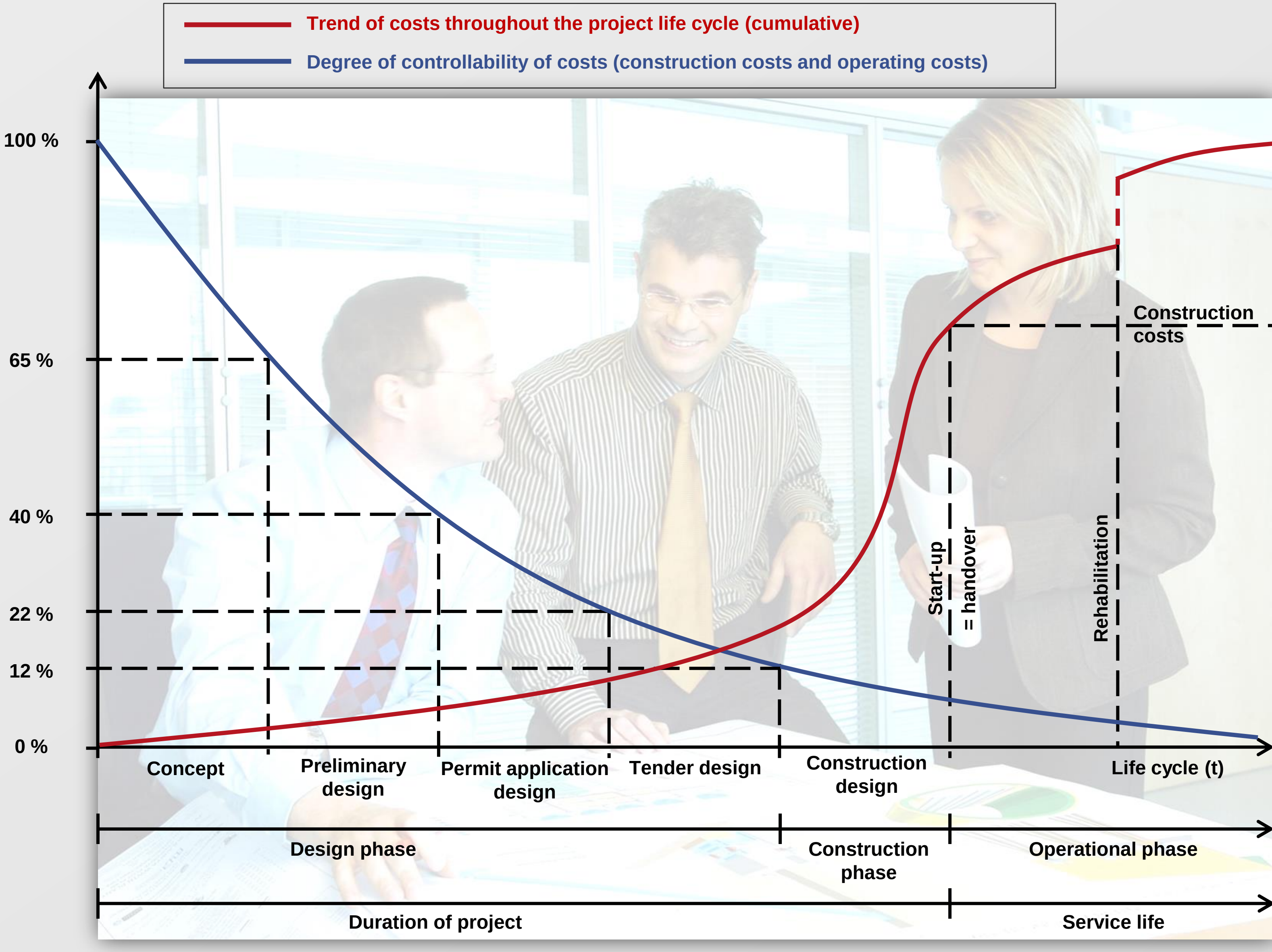
■ Service Portfolio

Decision Gates

Project Life Cycle	Appraise	Select	Define	Execute	Operate	Close
	Business Identification	Project Framing	Project Definition	Project Realisation	Business Control	Business Closure
ILF Services	Pre-/ Feasibility Studies	Due Diligence	Permit Application Design	Supply Chain Management	Operations Audit	Due Diligence
		Conceptual Design	Basic Design, FEED, Tender Design	Detailed Design	Due Diligence	Decommissioning Planning
		Environmental & Social Impact Assessment	Environmental & Social Impact Assessment	Design Review	Optimisation Studies	
		Execution Strategies	Project Management	Project Management	Modification Planning	
			Procurement	Construction Supervision	Rehabilitation Planning	
			Documentation for Investment Decision	Commissioning & Trial Operation	Maintenance Support	

Trend of project costs



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