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# **Multi-Layer Shotcrete Design for Tunnel Construction**

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## **1. ABSTRACT**

Shotcrete is an essential support element for conventionally driven tunnels. Traditionally shotcrete is applied in multiple layers for construction reasons, but for the design the lining is considered as monolithic. This is acceptable, in case the time lag between the application of each shotcrete layer is short, corresponding to one construction step. A different situation occurs, when an additional shotcrete layer is applied with a large delay. In that case the system consists of a pre-loaded and a stress-free layer and needs to be designed accordingly. Currently there is no explicit design procedure incorporated in the design codes, but only recommendations for design, such as relevant codes to be applied and the requirement to consider the pre-loading conditions of the first shotcrete layer. The paper presents and discusses a standard-conform (Eurocode 2) method for design of a concrete cross section consisting of two layers. The method is based on the assumption of full bond between the layers allowing full transfer of shear stress. The design procedure includes the check of strains in the relevant fibres of cross section, i.e. top and bottom fibres of the combined cross section, as well as the interface fibre between the layers. As result a bending moment – axial force interaction diagram of additional bearing capacity of the two layer cross section can be drawn for specific pre-loading conditions of the first shotcrete layer. Parametric study of pre-strain conditions of the first shotcrete layer confirmed, that a strengthening of the cross section is reasonable only for cases, when the capacity of the first shotcrete layer is not highly utilized. The additional bearing capacity of a two layer cross section with highly utilized first layer is very limited.

## **2. INTRODUCTION**

Shotcrete linings have been applied successfully in a large number of tunnel projects within the last decades all around the world. While up to the 1970's the structural design of the shotcrete lining was based mainly on experience gathered throughout the construction and some simplified analyses in the following years the application of the Finite Element Method lead to much more sophisticated design and more accurate estimation of deformations and stress state in the shotcrete lining. This was amongst others achieved by considering the time and construction sequence - dependent development of the deformations as well as by applying simplified time dependent material laws for shotcrete. This structural analysis with determination of sectional forces is quite a complex topic but not discussed in this paper.

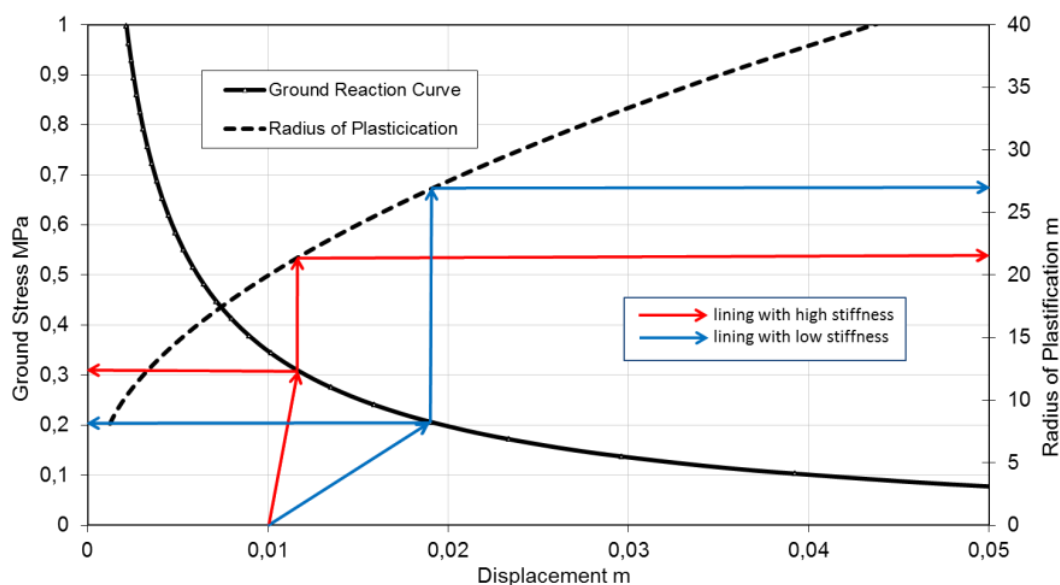
The design verification as such is commonly done by using the methods as stated in Eurocode 2 (EC 2) for ultimate limit state (ULS) and serviceability limit state (SLS). This design verification becomes even more complex for cases in which during a first

construction stage one shotcrete layer is applied and loaded and only later, additional stress free layers are installed in order to carry further loads caused by later construction stages. This design verification is described in detail for a two layered shotcrete lining within the next paragraphs.

### 3. DESCRIPTION OF THE PROBLEM

For shotcrete lined tunnels the designer strives to optimize the lining thickness by utilizing the load bearing capacity of the surrounding ground, but still limiting its deformation and plastification to an acceptable amount. Lining and other support elements as well as the surrounding ground act structurally like a system of parallel springs. The stiffer the lining is designed the more loads it will attract. This can easily be shown with a convergence confinement diagram depicted in Figure 1. While the blue line shows a lining with low stiffness (thin lining) and thus higher deformations but less load on the lining, the red line represents a lining with higher stiffness (thicker lining) resulting in more load for the lining. For this reason it makes sense to apply shotcrete in various layers following individual construction stages and not to apply the whole shotcrete thickness at once.

It also can be seen that with the stiff lining the radius of plastification is less than for lining with low stiffness.



**Figure 1: Ground Reaction and Support Curves for a circular tunnel with high and low stiffness of the lining**

Tunnel designers frequently come across such cases e.g. when cross ways between two main tunnels need to be installed or a second, parallel tunnel is driven while the first tunnel is already in place. Figure 2 shows two cases of strengthening the first shotcrete lining. Left an additional layer will be installed (stage with reinforcement in place shown). Right part shows installed longitudinal reinforcement above the future opening for cross ways on both sides.



**Figure 2: Subsequently added strengthening of the shotcrete layer**

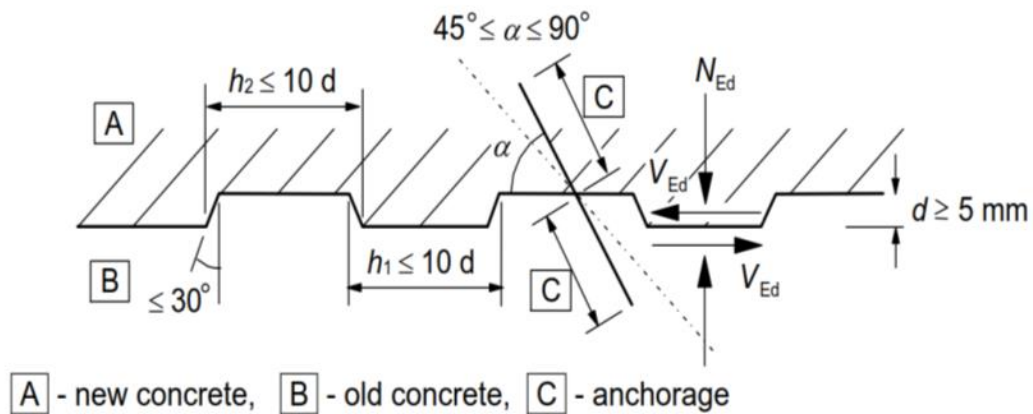
#### 4. INTERACTION OF TWO SHOTCRETE LAYERS

For structural reasons it is obviously advantageous that both layers act together as one homogeneous cross section. The bending stiffness is much higher in case of one single homogeneous cross section (no slip between layers) than for independent cross sections (slip between layers).

A precondition for this behaviour is a rigid bond between the layers which allows the transfer of shear stress in between them.

Nevertheless it has to be verified that the shear resistance at the interface between the layers is larger than the shear stress. It can be assumed that the surface of shotcrete in general is “rough” according to EC 2 which is a surface with at least 3 mm roughness at about 40 mm spacing.

For cases where the “rough” surface is not sufficient an indented surface can be considered which provides even more shear resistance. In such cases the shotcrete surface has to comply in average with Figure 3.



**Figure 3: Indented construction joint – EC 2**

Such an indented joint can subsequently be constructed, e.g. by a high-pressure water jet (see Figure 4).



**Figure 4: Indented construction joint - performed**

In cases with high shear force interface reinforcement may be required. This is to be designed in accordance with EC 2 and needs to be installed while implementing the first shotcrete layer. Figure 5 shows phases of construction and implementation of shear dowels.



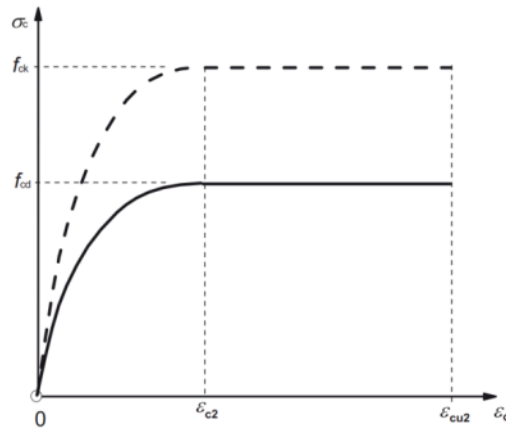
**Figure 5: Construction shear dowels**

Independent of the roughness the surface shall be cleaned with high-pressure water jet before applying the next shotcrete layer.

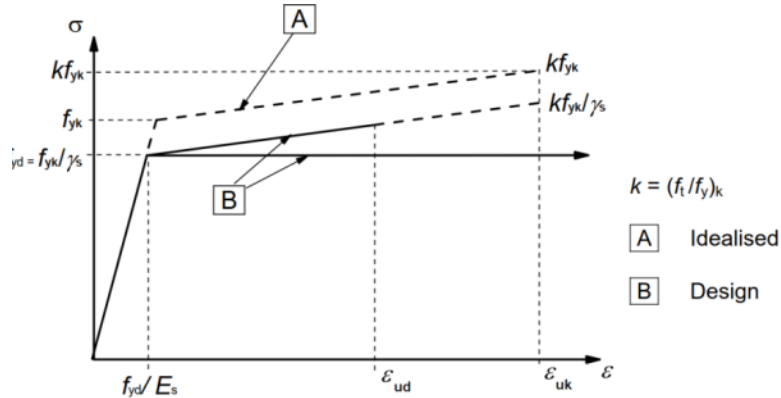
Within this paper it is assumed that full bond between the shotcrete layers is reached.

## 5. ULS DESIGN FOR BENDING WITH AXIAL FORCE IN GENERAL

The standard design according to EC 2 takes into account the parabola – rectangle diagram for concrete under compression and the bilinear stress – strain relation for steel as shown in Figure 6 and Figure 7. The important strain values shown in both diagrams are for concrete  $\varepsilon_{c2} = -2,0 ‰$  and  $\varepsilon_{cu2} = -3,5 ‰$  as compression strains (values apply for concrete classes C12/15 to C50/60) and for reinforcement steel  $\varepsilon_{uk} = -25,0 ‰$  as tension strain (applies for all reinforcement strength classes). It must be noted, that these stress strain curves are not to be used for the structural analysis but only for the design verification.



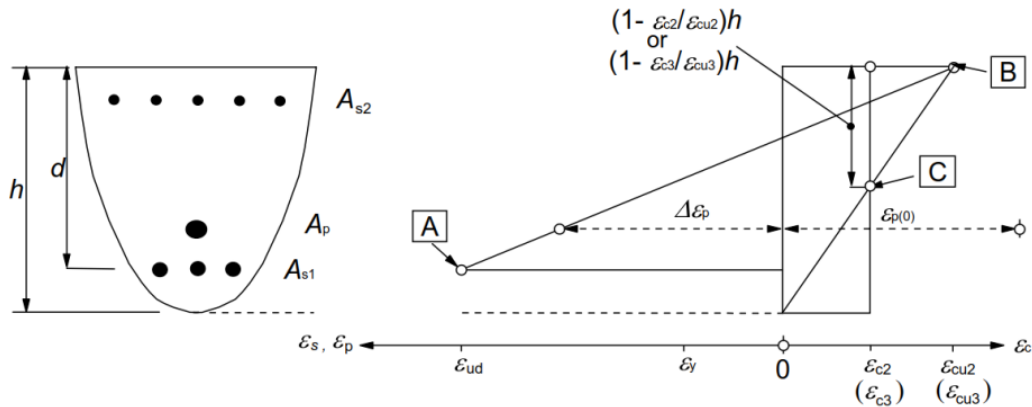
**Figure 6: Parabola – rectangle diagram for concrete under compression**



**Figure 7: Design stress strain diagram for reinforcing steel (tension and compression)**

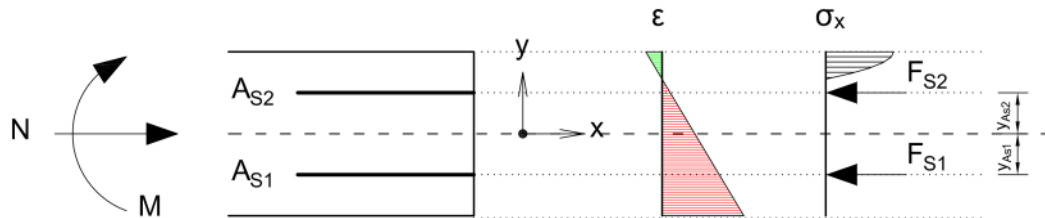
The assumptions for the design are:

- 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 according to Figure 6 and Figure 7



**Figure 8: 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 in Figure 8) until equilibrium between calculated actions and the inner forces derived from the strain state is reached.



**Figure 9: Strain and stress state for design of single concrete cross section**

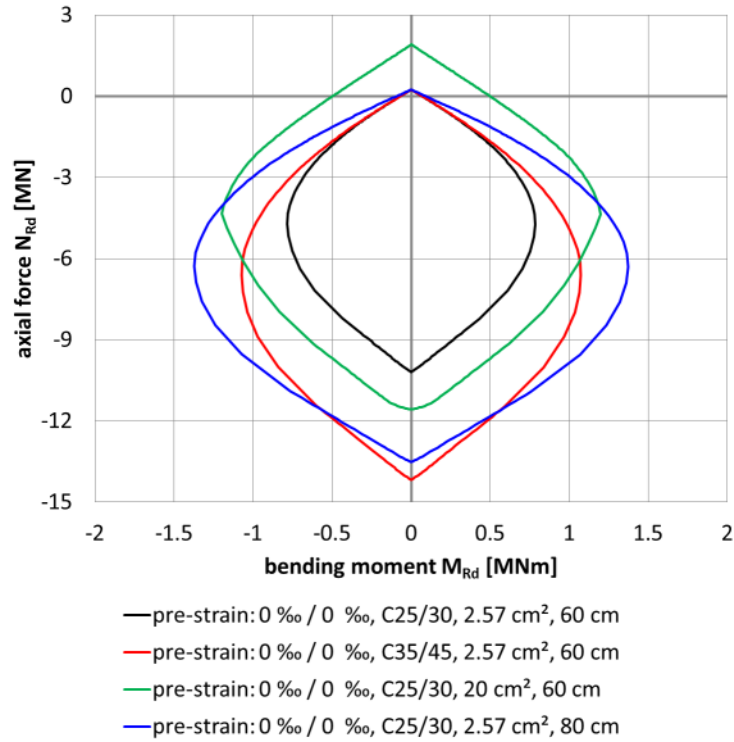
$$\Sigma H = 0$$

$$N = \int_A \sigma_x \cdot dA + F_{S1} + F_{S2}$$

$$\Sigma M = 0$$

$$M = \int_A \sigma_x \cdot y \cdot dA + F_{S1} \cdot y_{A_{S1}} - F_{S2} \cdot y_{A_{S2}}$$

The result can be drawn in bending moment – axial force interaction diagram (M-N diagram) as shown in Figure 10. For comparison the influence of the main parameters – concrete strength, reinforcement and cross section height – is presented.



**Figure 10: M-N interaction diagram**

## 6. TWO LAYER SHOTCRETE DESIGN

The difficulty arises as a part of the cross section, the first shotcrete layer, is already loaded while the newly applied shotcrete, the second layer, is stress free.

In a first step the stress – strain state in the first shotcrete layer needs to be determined. This typically is not the one resulting from the design, because not exactly the reinforcement as calculated will be installed. The stress state is found in an iterative procedure in a way that the strain in the first shotcrete layer is varied until equilibrium with the actions is reached.

In order to determine the additional capacity of the whole cross section additional strain ( $\Delta\varepsilon$ ) is applied under the assumption that plane sections remain plane in order to reach the limit strains according to EC 2 for concrete compression and for steel in tension (refer to Figure 8) in the top, bottom and the interface (between first and second layer) fibre (following design principles according DIN 18551). This additional strain  $\Delta\varepsilon$  is added to the already existing strain  $\varepsilon_0$  of the first layer resulting in total strain  $\varepsilon_{tot}$ . With this approach M-N diagrams for the additional load can be drawn.

$$\Sigma H = 0$$

$$N = \int_{A_{1+A2}} \Delta\sigma \cdot dA + \Delta F_{S1} + \Delta F_{S2} + F_{S3} + F_{S4}$$

$$\Sigma M = 0$$

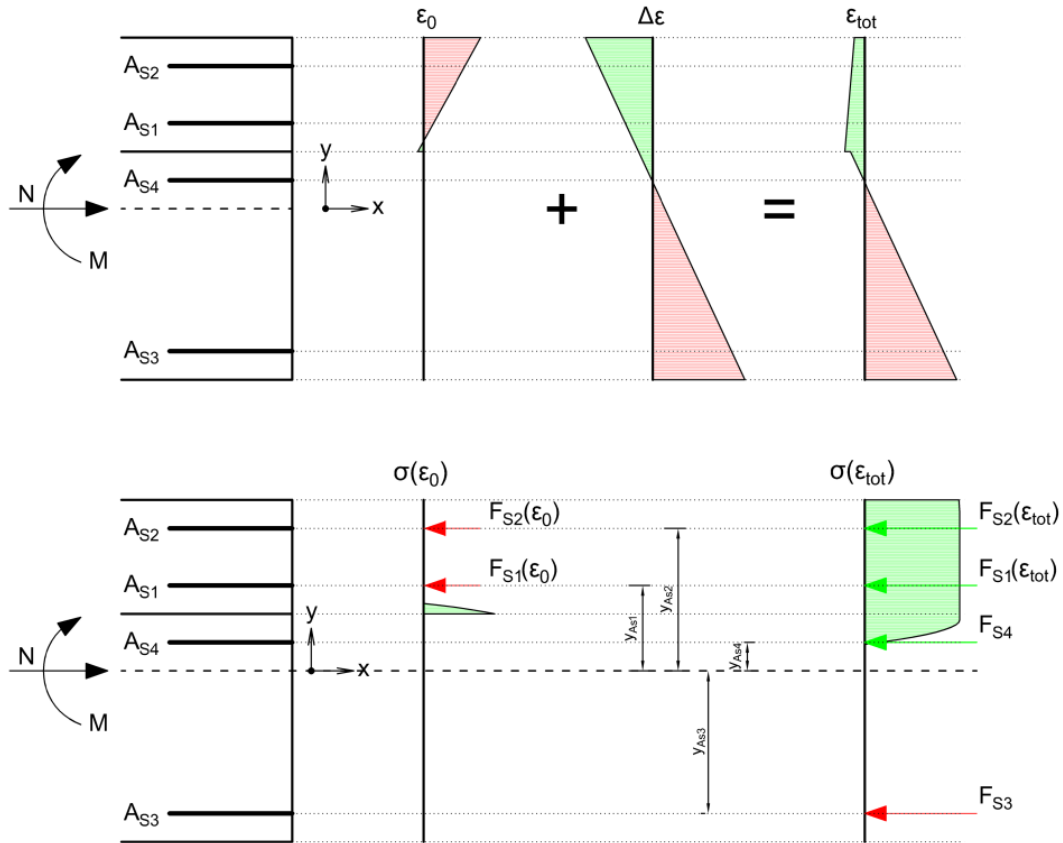
$$M = \int_{A_{1+A2}} \Delta\sigma \cdot y \cdot dA + \Delta F_{S1} \cdot y_{A_{S1}} + \Delta F_{S2} \cdot y_{A_{S2}} + F_{S3} \cdot y_{A_{S3}} + F_{S4} \cdot y_{A_{S4}}$$



$$\Delta\sigma = \sigma(\varepsilon_{tot}) - \sigma(\varepsilon_0)$$

$$\Delta F_{S1} = F_{S1}(\varepsilon_{tot}) - F_{S1}(\varepsilon_0)$$

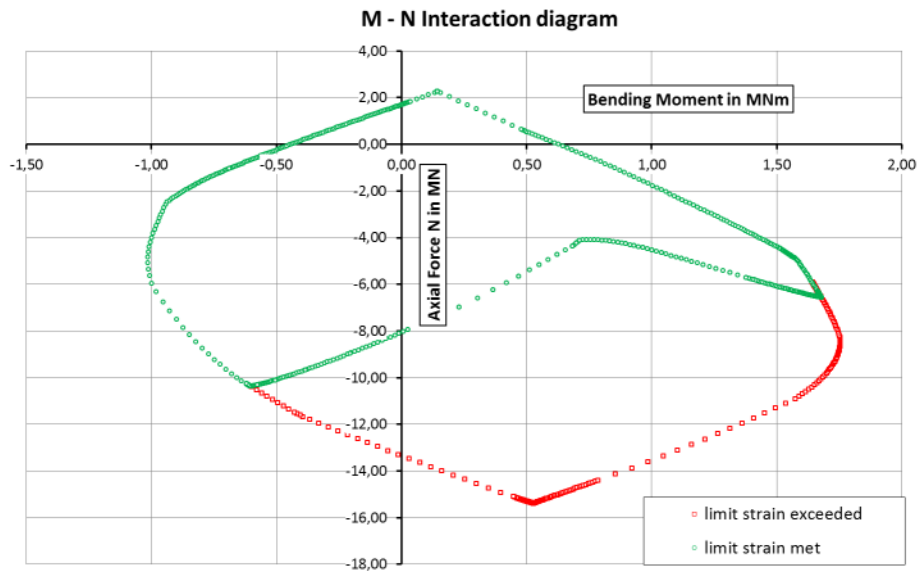
$$\Delta F_{S2} = F_{S2}(\varepsilon_{tot}) - F_{S2}(\varepsilon_0)$$



**Figure 11: Strain and stress state for design of composite concrete cross section**

In case only the limit strains in the top and bottom fibres are evaluated (but not the interface fibre) the strain in the interface fibre may exceed the limit strain (unallowable strain) as shown in Figure 12. After eliminating all unallowable strain combinations in the interface fibre, all remaining combinations fulfil the criteria as defined previously (EC 2 strain limits). It already can be seen that the additional capacity is no more symmetric. The reason is that the additional strain to reach the limit strain is different between top and bottom fibre due to the pre strain of the first shotcrete layer.

The whole cross section (first and second layer) is assumed to behave under the assumptions of EC 2 as described in previous sections. The most important assumption for this case is that plane sections remain plane under the new load, although one part of the cross section is already loaded.

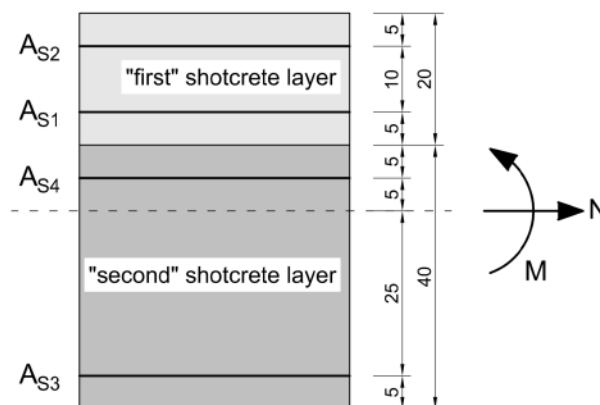


**Figure 12: M-N combinations for allowable and unallowable (limit strain exceeded) strain states**

## 7. DISCUSSION OF SPECIFIC RESULTS

### 7.1. General case

In the following figures characteristic examples are shown and discussed. For the investigated cases the basic input data, geometry and material parameters remain the same, see Figure 13 and Table 1. Additionally to the base case (virgin cross section) without pre-strain, three pre-strain states of the first shotcrete layer are investigated considering low utilization of the concrete section (case 1), maximum utilization in accordance to EC 2 (case 3) and a moderate utilization (case 2). M-N interaction diagrams are derived as described in previous sections. The different cases of pre-strain conditions of the first shotcrete layer are listed in Table 2.



**Figure 13: Base case of composite cross section and definition of positive sectional forces**

Table 1: Input data for base case

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

Table 2: Cases of pre-strain conditions of first shotcrete layer

Case	1a	2a	3a
$\epsilon_{top} [\text{‰}]$	-0,1	-0,8	-3,5
$\epsilon_{bottom} [\text{‰}]$	1,0	12,5	25
pre-strain distribution			

Case	1b	2b	3b
$\epsilon_{top} [\text{‰}]$	1,0	12,5	25
$\epsilon_{bottom} [\text{‰}]$	-0,1	-0,8	-3,5
pre-strain distribution			

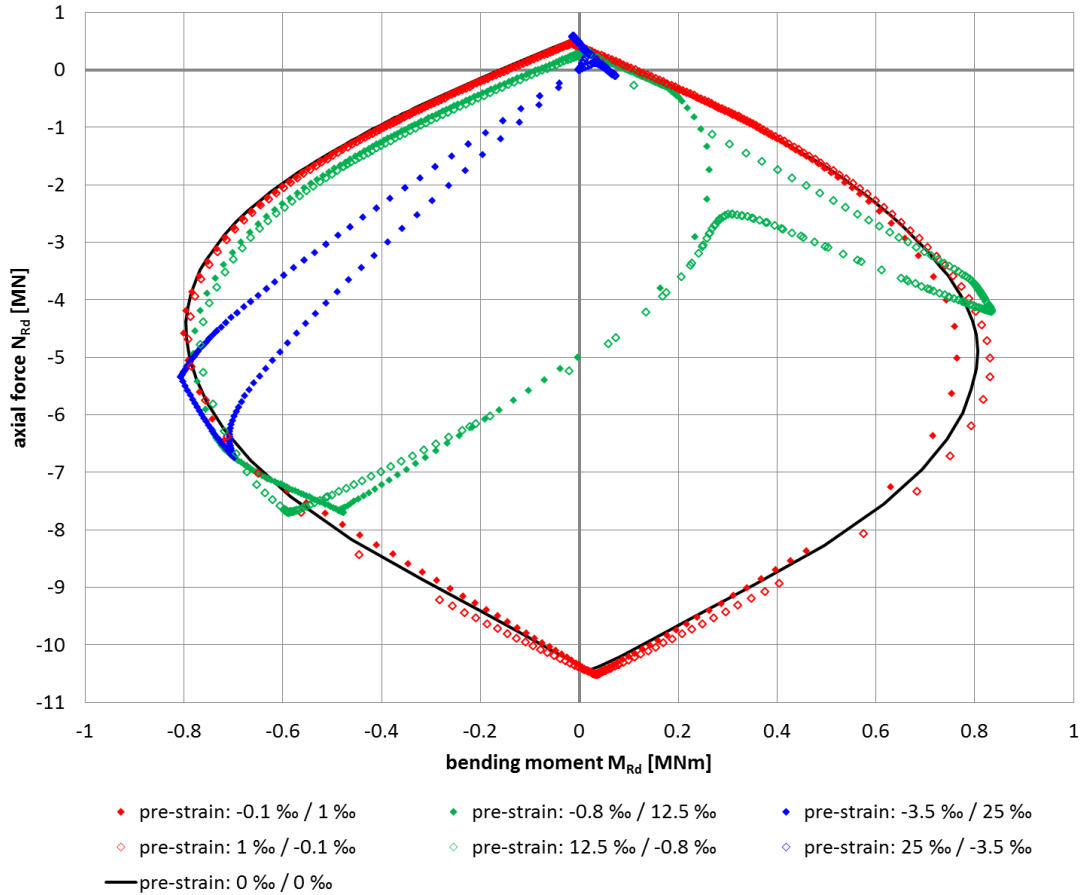
Figure 14 shows seven interaction diagrams considering the base case without any pre-strain of the first shotcrete layer (virgin cross section) and three pairs of the investigated cases (see Table 2).

It becomes quite obvious that for case 1 (low utilization) the interaction diagram is very similar to the base case (virgin cross section) without any pre strain. The higher the utilization of the first shotcrete layer the lower the additional bearing capacity of the combined cross section will be. In case 3 (maximum utilization) only very specific M-N combinations (within the blue region) can be applied. Due to the uncertainties in the structural analysis such design approach with very high utilization of the first shotcrete layer is not acceptable.

It also can be seen that there is more additional capacity for cases with negative bending moment for the combined cross section.

Additionally to the general case further variations for the pre-strain conditions are investigated. Variant 1 targets the influence of the concrete strength of the second shotcrete layer (C25/30, C30/37 and C35/45). Variant 2 targets the influence of the reinforcement

amount in the first and second shotcrete layers. A minimum, a moderate and a very high amount of reinforcement are investigated (see Table 3). Variant 3 targets the influence of the thickness of the second shotcrete layer (30 cm, 40 cm and 50 cm).



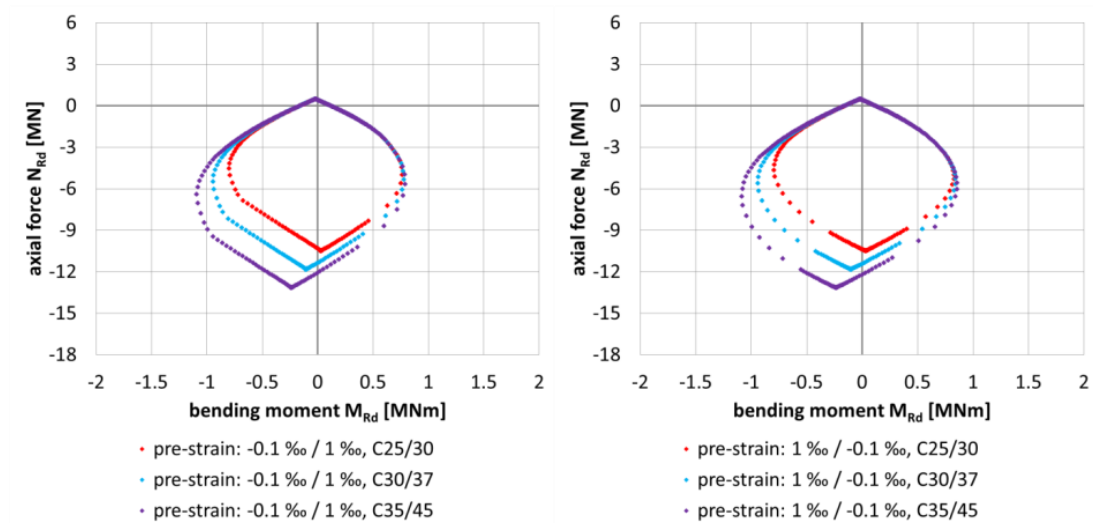
**Figure 14: General case – M-N interaction diagrams**

Table 3: Investigated reinforcement amounts of shotcrete layers

Shotcrete layer	First shotcrete layer		Second shotcrete layer	
	$A_{S1}$ [cm <sup>2</sup> ]	$A_{S2}$ [cm <sup>2</sup> ]	$A_{S3}$ [cm <sup>2</sup> ]	$A_{S4}$ [cm <sup>2</sup> ]
Minimum amount (providing of ductility)	2.57		2.57	
Moderate amount	10		20	
Very high amount (50% of $A_{s,max}$ according to EC 2)	20		40	

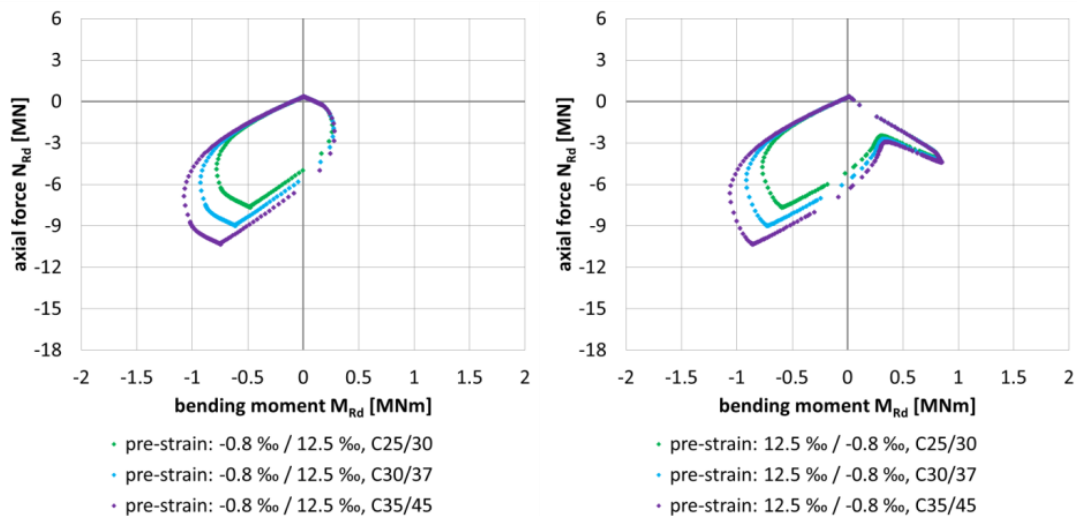
## 7.2. Variant 1 – influence of the concrete strength

While the typical shotcrete strength has been C25/30 during the previous decades the shotcrete technology has been improved significantly so that the application of even C35/45 is possible meanwhile. It can be seen below that with increasing concrete strength the additional bearing capacity increases as well, mainly with axial compressive force and negative bending moment.



**Figure 15: M-N interaction diagrams – Influence of the concrete strength – low utilization**

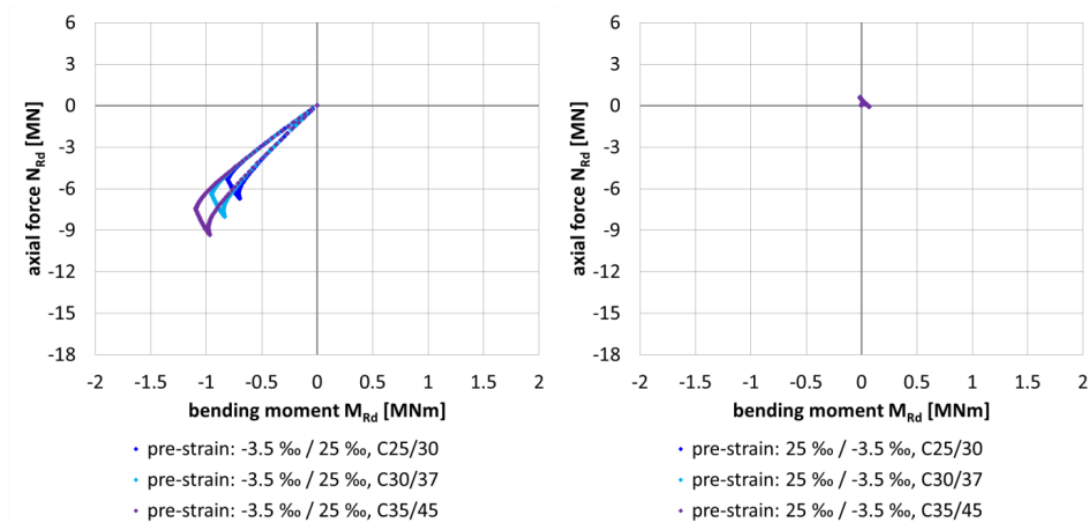
Figure 16 shows that for cases with pre-strain of 12,5 ‰ (tensile strain) in the top fibre and -0,8 ‰ in the interface fibre higher additional positive bending moments can be applied. It is emphasised that such design is not considered as acceptable due to the narrow range of the interaction curve in this area and the uncertainties of the structural analysis.



**Figure 16: M-N interaction diagrams – Influence of the concrete strength – moderate utilization**

Increasing capacity for the whole cross section is also identified in cases with maximum utilization of the first shotcrete layer. Nevertheless this design is not considered as acceptable due to the uncertainties of the structural analysis. The pre-strain combination 25 ‰ in the top fibre and -3,5 ‰ in the interface fibre allows for only very limited additional strain and in addition those additional strain is mainly in tension. Thus the main contribution

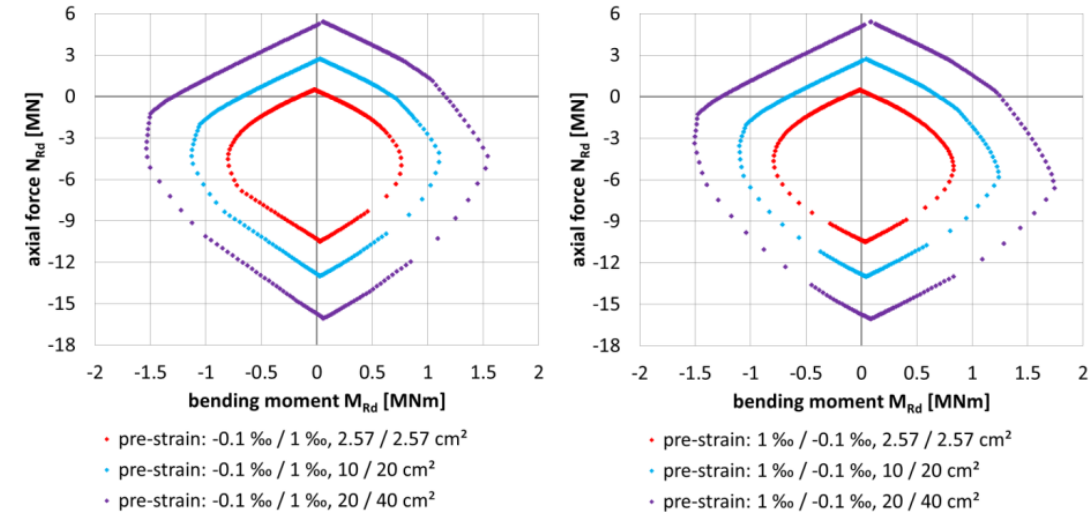
to the additional bearing capacity results from the reinforcement and not from the concrete for which reason the additional bearing capacity is very limited.



**Figure 17: M-N interaction diagrams – Influence of the concrete strength – maximum utilization**

### 7.3. Variant 2 – influence of the reinforcement amount

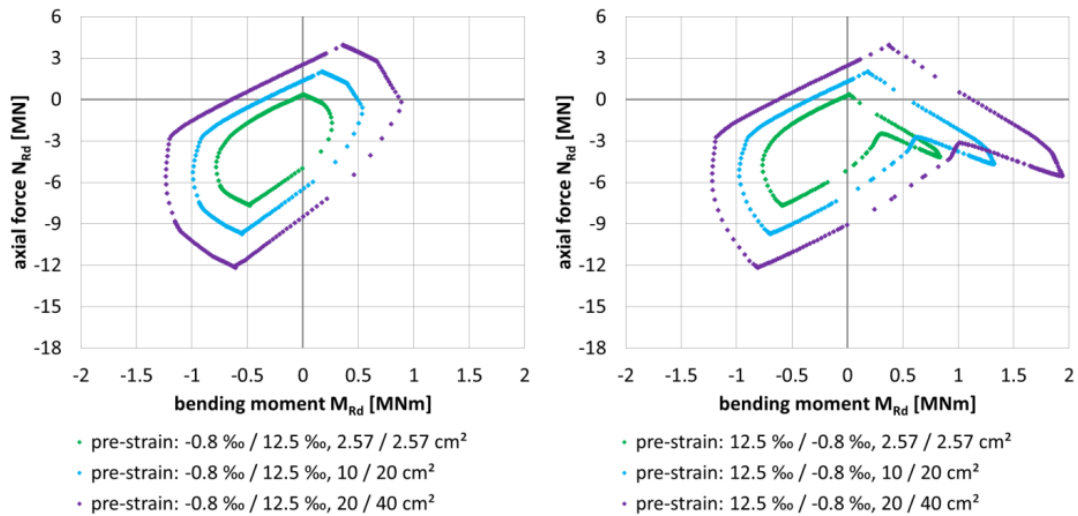
Additional reinforcement provides higher capacity not only for the compressive axial forces, but for low and moderate utilization (Figure 18 and Figure 19) for tensile axial forces also. For a low utilization the interaction diagram is almost symmetric (refer to Figure 18).



**Figure 18: M-N interaction diagrams – Influence of reinforcement amount – low utilization**

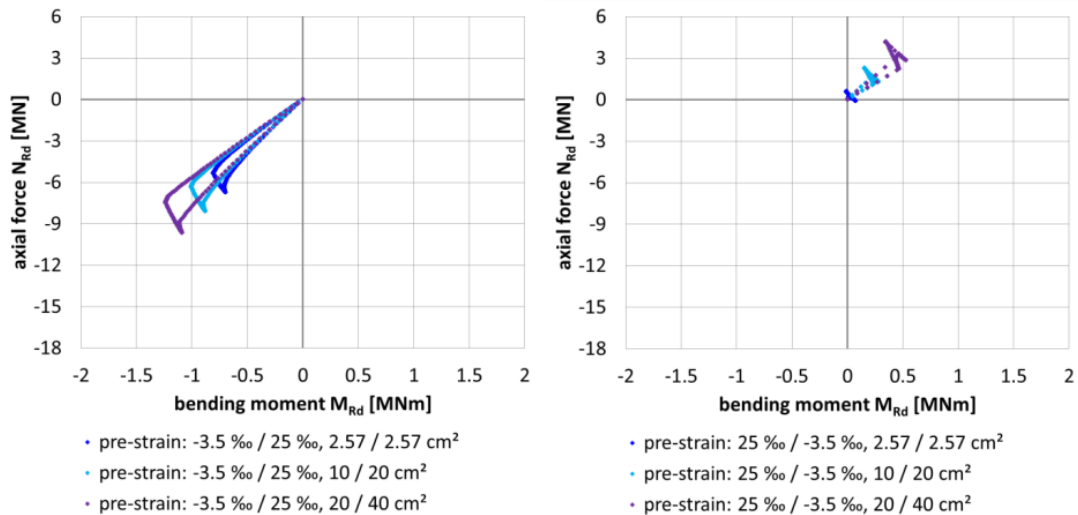
Figure 19 shows that for cases with pre-strain of 12,5 ‰ (tensile strain) in the top fibre and -0,8 ‰ in the interface fibre additional high positive bending moments can be applied (up to

1,9 MNm). It is emphasised that such design is acceptable only then, when the range of axial force corresponds to the accuracy of the structural analysis.



**Figure 19: M-N interaction diagrams – Influence of reinforcement amount – moderate utilization**

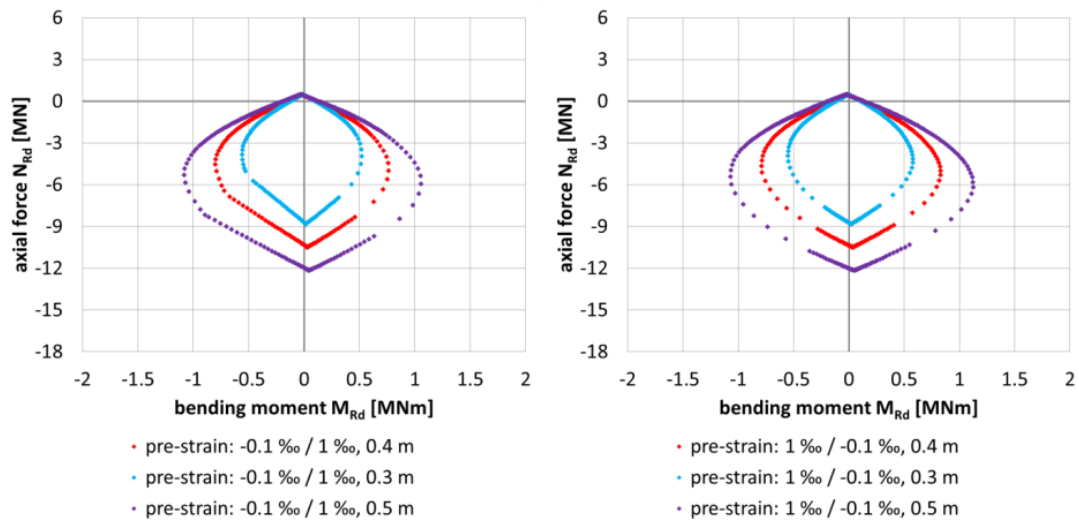
Similar as for higher concrete strength an increase in capacity for the whole cross section is also identified in cases with maximum utilization of the first shotcrete layer. Nevertheless this design is not considered as acceptable due to the uncertainties of the structural analysis.



**Figure 20: M-N interaction diagrams – Influence of reinforcement amount – maximum utilization**

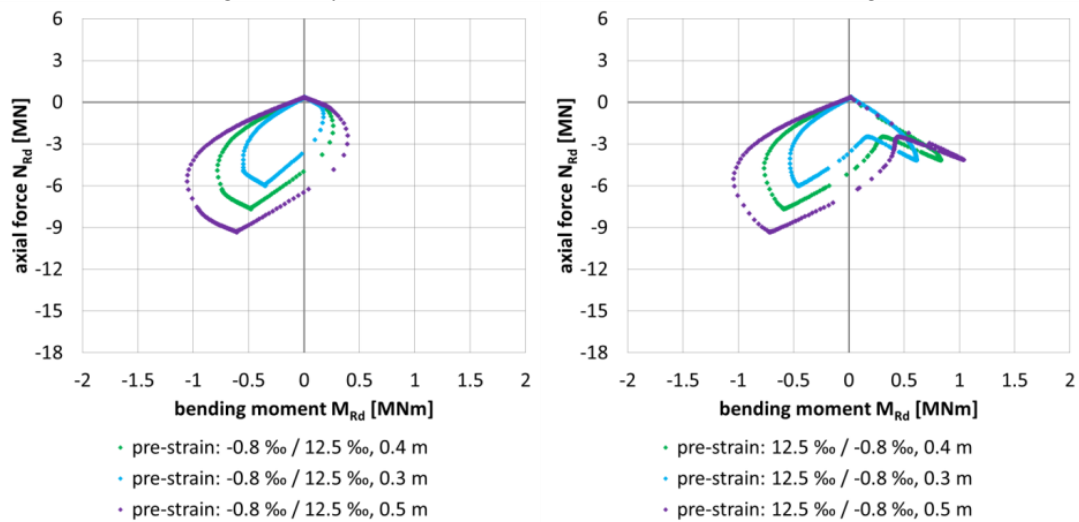
#### 7.4. Variant 3 – influence of the thickness of the second shotcrete layer

For a low utilization (Figure 21) the additional capacity grows symmetric as in case of higher reinforcement. The main difference is that only for compressive axial force and for tension no additional capacity can be achieved with larger thickness of the cross section.



**Figure 21: M-N interaction diagrams – Influence of cross section thickness – low utilization**

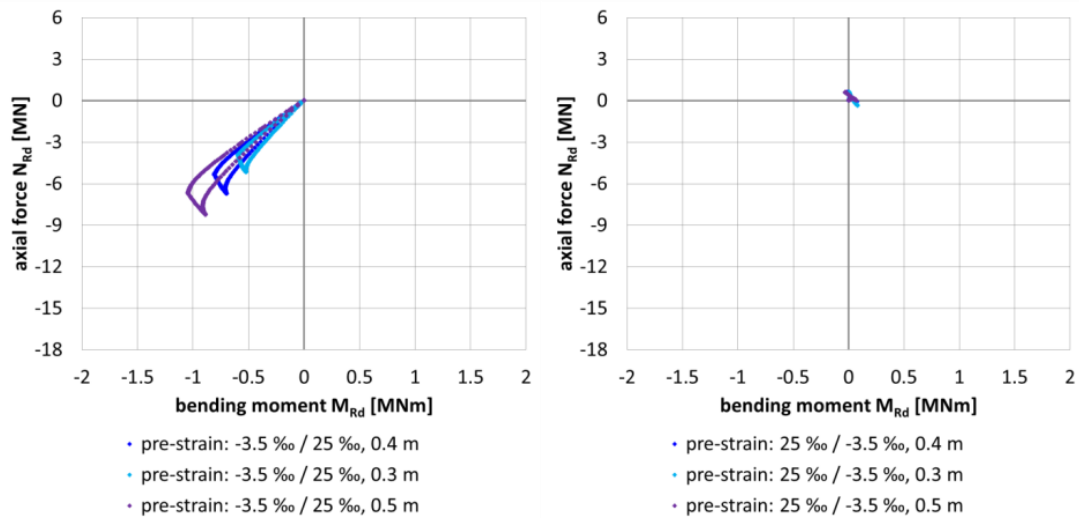
On the other hand for a moderate (Figure 22) and maximum utilization (Figure 23) the effect of cross section height is very similar as in case of different concrete strength.



**Figure 22: M-N interaction diagrams – Influence of cross section thickness – moderate utilization**

As already previously stated an increasing capacity for the whole cross section is identified in cases with maximum utilization of the first shotcrete layer. Nevertheless this design is not considered as acceptable due to the uncertainties of the structural analysis.





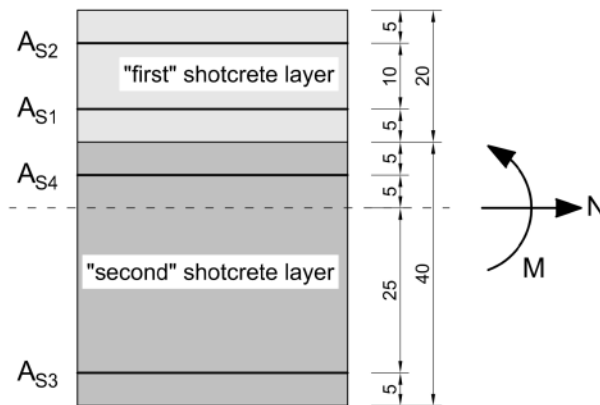
**Figure 23: M-N interaction diagrams – Influence of cross section thickness – maximum utilization**

### 8. EXAMPLE

In an example the utilization of the proposed design procedure is demonstrated. The general design procedure consists of following steps:

1. Calculation of internal forces in the first shotcrete layer – phase 1 (without second shotcrete layer)
2. Cross section design – calculation of required reinforcement
3. For specified reinforcement (not necessarily equal to  $A_{s,req}$  from step 2) calculation of pre-strain state
4. Calculation of additional internal forces in the combined cross section – phase 2
5. Determination of additional load capacity of combined cross section and evaluation
6. Possible adaptation of parameters (lining thickness of layer 1 and 2, concrete strength, reinforcement)

For the example calculation the same cross section parameters are used as considered in previous sections (see Figure 24). Used concrete strength is  $f_{ck} = 25$  MPa and reinforcement strength  $f_{yk} = 550$  MPa.



**Figure 24: Combined cross section for example application**

Step 1:

The design actions in the first shotcrete layer with a thickness of 20 cm are  $M = 70$  kNm and  $N = -700$  kN.

Step 2:

The required reinforcement area is calculated as  $A_{s1} = 3.1$  cm<sup>2</sup> and  $A_{s2} = 0$  cm<sup>2</sup>. The reached strain state in top and interface fibre is  $\epsilon_{top} = -3.35$  ‰ and  $\epsilon_{interface} = 7.19$  ‰.

Step 3:

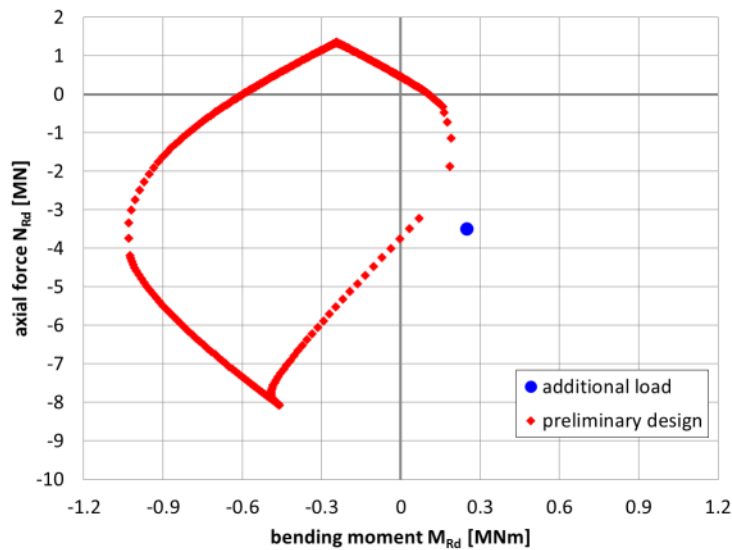
For practical reasons a symmetric reinforcement is considered with  $A_{s1} = A_{s2} = 3.35$  cm<sup>2</sup>. This leads to a different, more favourable, strain state than in the design situation resulting in  $\epsilon_{top} = -2.21$  ‰ and  $\epsilon_{interface} = 4.09$  ‰.

Step 4:

The additional internal forces in the combined cross section are assumed with  $\Delta M = 250$  kNm  $\Delta N = -3500$  kN and.

Step 5:

For the preliminary design the additional capacity is not sufficient for the additional internal forces yet and an adaptation of combined cross section is necessary. The M-N interaction diagram is shown in Figure 25.

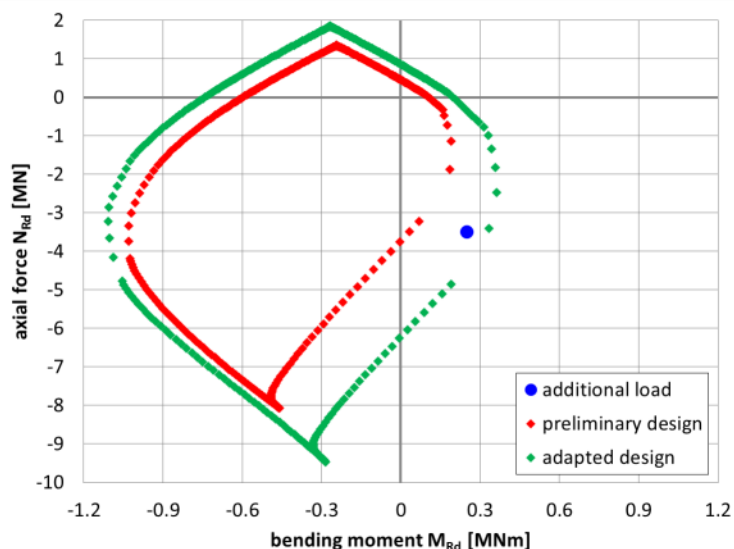


**Figure 25: M-N interaction diagram for preliminary design**

Step 6:

As concluded in section 7.2 an adaptation of the concrete strength would not have the desired effect on the additional capacity (additional capacity mainly for negative bending moments), hence an adaptation of reinforcement is performed. A symmetric reinforcement is considered with  $A_{s1} = A_{s2} = 6.0$  cm<sup>2</sup>. This leads to a lower strain state than in step 3 resulting in  $\epsilon_{top} = -1.7$  ‰ and  $\epsilon_{interface} = 2.58$  ‰.

Consequently for the adapted design the additional capacity is now sufficient for the additional internal forces. The M-N interaction diagrams for preliminary and adapted design are shown in Figure 26.



**Figure 26: M-N interaction diagram for preliminary and adapted design**

## 9. CONCLUSIONS AND FUTURE RESEARCH

A standard-conform (EC2) method for design of a concrete cross section consisting of two layers is presented and discussed. One layer is loaded before the second layer is applied, hence pre-loading (pre-strain) of the first layer needs to be considered in the design procedure of two layer section. The design procedure is based on following assumptions and criteria:

- Full bond between the two shotcrete layers is assumed. This condition allows for maximum bearing capacity of the combined cross section. With a reduced bond (or even slip) between the concrete layers the system would achieve less bearing capacity, since the transfer of load into the second layer would be limited by the shear capacity of the interface between layers.
- None of the three main fibres (top, interface and bottom) and thus no fibre of the combined cross section shall exceed the limit strain as per EC 2. It is crucial to check the strains in the interface fibre, since this is very often the governing fibre for determination of the bearing capacity.

Parametric studies of pre-strain conditions of the first shotcrete layer confirmed, that a strengthening of the cross section is reasonable only for cases, when the capacity of the first shotcrete layer is not highly utilized. The additional bearing capacity of a two layer cross section with highly utilized first layer is very limited as hardly any further strain can be applied.

General interaction diagrams for a combined cross section cannot be provided due to unlimited number of pre-strain combinations. For each individual pre-strain condition a special calculation is necessary.

For the future research some suggestions are formulated:

- Interaction diagrams of total bearing capacity for given pre-strain conditions of the first shotcrete layer will allow a comparison of different combinations of boundary conditions (e.g. thickness of both layers maintaining same total thickness, variation of reinforcement area and concrete class).
- The discussed design approach can be extended for more than two layers but will become very complex
- The discussed design approach can be extended for fibre reinforced concrete as well. The tensile capacity of the concrete will lead to an increased bearing capacity of the cross section to some limited extent.
- The discussed design approach is based on theoretical calculations. It might be useful to verify and document the behaviour of a layered concrete cross section in experiments.

## **10. REFERENCES**

- EN 1992-1-1: Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings.
- DIN 18551: Sprayed concrete – National application rules for series DIN EN 14487 and rules for design of sprayed concrete constructions