University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Engineering Structures and Materials, specialization Civil Engineering Structures	Spring semester, 2018 Open / ~~Restricted~~ access
Writer: Bjarte Hodne	………………………………………… (Writer's signature)
Faculty supervisor: Samindi Samarakoon External supervisor(s): Bjørnar Owren	
Title of thesis: A study on effect of tendon layouts in post-tensioned flat slabs	
Credits (ECTS): 30	
Key words: Post-tensioned flat slabs Tendon layout	Pages: 98 + enclosure: 117 Stavanger, 14.06.2018

Abstract

The use of post-tensioned flat slabs is sufficient when large spans or thin floors are desired. The most used system today is to place unbonded tendons concentrated over the supports in one direction and distribute them across the whole slab in the other direction.

This thesis addresses the influence the tendon layout in flat slabs has on the results. Analysis of three different flat slabs with five different tendon layouts in addition to one without any tendons has been done. The tendon layouts vary in the number of tendons that are distributed across the whole slab, the number of tendons that are concentrated over supports, and whether they are placed in the longest or shortest span direction. The calculations are made by hand, and by the programs ADAPT-Floor Pro and FEM-Design 17. Results from the programs has also been compared to enlighten differences.

The main difference between ADAPT and FEM-Design is that ADAPT uses design sections which makes it sufficient for the design process of prestressed structures. The program is based on averaging the actions on each design section, which has the width of half the span to both sides of the columns. The feature of modelling unbonded tendons in FEM-Design was new in version 17 released in January 2018. The feature cannot be used for design but are for analysis purpose only. FEM-Design does not use design sections, and some of the results are hence not directly comparable with ADAPT and hand calculations.

Results from the analysis shows that a higher portion of tendons that are concentrated instead of distributed, stresses caused by other structural loads is counteracted best. The tensile stresses at columns is most likely to cause cracking of the concrete, and with 100% of the tendons concentrated, the total service stresses here will be the lowest. The layout with all tendons concentrated also has the best results in terms of deflections. This is because the distributed tendons will for small areas cause downward forces in spans, while these downward forces of the concentrated tendons will be directly over the supports.

A tendon layout with no distributed tendons may nevertheless not be the most sufficient one because the slab between the supports, where no tendons are placed, may not have enough bending moment capacity. This tendon layout will hence require extra reinforcement in spans to be a sufficient design. The layout where the tendons are distributed and concentrated in both directions does fit the bending moment distribution the best, but the amount of weaving of tendons in spans will increase the construction time, and hence make it uneconomical.

Preface

This thesis is written as completion of the Master of Science in Engineering Structures and Materials at the University of Stavanger. It is written in the period January – June 2018.

The topic was chosen based on that modelling of post-tensioned structures was a new feature to the software FEM-Design in January 2018. By choosing this topic I would get to work with and investigate the use of this feature. Writing this thesis has increased my knowledge regarding prestressed structures in addition to the use of the programs FEM-Design and ADAPT.

I would like to thank the Norconsult department in Stavanger for the possibility to use an office space and to borrow a computer in the writing process. I would also like to thank for the possibility to use programs and literature the company accesses.

I would like to thank my internal supervisor at the University of Stavanger, Samindi Samarakoon, for helping me when I had questions and for checking my calculations. I would also like to thank for the literature I got to borrow.

I would like to thank my external supervisor at Norconsult, Bjørnar Owren, for help regarding FEM-Design.

I would like to thank Jeff Steelhammer at the Norconsult department in Bergen for helping me with the use of the ADAPT software.

I would also like to thank my wife for motivating me and taking good care of our beautiful daughter during this period.

Stavanger, June 2018

Bjarte Hodne

Table of contents

Abstract iii

Preface v

List of figures xi

List of tables xv

1 Introduction 1

1.1 Background 1

1.2 Scope of the thesis 1

1.3 Method 2

2 Theory 3

2.1 Flat slabs 3

2.2 Prestressed concrete 4

2.2.1 Post-tensioning 5

2.2.2 Load balancing 8

2.2.3 Prestressing force 12

2.3 Analysis and design guidelines for prestressed concrete members with unbonded tendons 17

2.3.1 Material 17

2.3.2 Durability 18

2.3.3 Initial determination of thickness for post-tensioned flat slabs 19

2.3.4 Minimum reinforcement 20

2.3.5 Tendon spacing 21

2.3.6 Analysis of flat slabs 23

2.3.7 Ultimate Limit State (ULS) 25

2.3.8 Serviceability Limit State (SLS) 31

3 Determination of conditions 37

3.1 Material ... 37

3.2 Design ... 38

4 Validation and comparison of FEM-results ... 39

4.1 Design ... 39

4.1.1 Load balancing - Tendon layout and profiles ... 40

4.2 Modelling ... 40

4.2.1 FEM-Design 17 ... 41

4.2.2 ADAPT-Floor Pro ... 42

4.2.3 Differences in the modelling and analysis process ... 43

4.3 Losses of prestress ... 44

4.3.1 Distributed tendons - Y-direction ... 44

4.3.2 Concentrated tendon - X-direction ... 46

4.3.3 Discussion ... 47

4.4 Deflection ... 51

4.4.1 Initial load combination ... 51

4.4.2 Quasi-permanent load combination ... 52

4.5 Stresses ... 53

4.5.1 Initial load combination ... 53

4.5.2 Quasi-permanent load combination ... 54

4.5.3 Discussion ... 55

4.6 Bending moment ... 57

4.6.1 Ultimate bending moment ... 57

4.6.2 Ultimate bending moment capacity ... 60

4.7 Calculation of shear capacity ... 61

5 Tendon layout analysis ... 63

5.1 Parameters ... 63

5.1.1 Flat slabs ... 63

5.1.2 Prestressing ... 64

5.1.3 Tendon layouts ... 65

5.2 Results & discussion ... 67

5.2.1 Deflections at SLS ... 67

5.2.2 Stresses at SLS ... 69

5.2.3 Bending moments at ULS ... 73

5.2.4 Shear at ULS ... 73

5.2.5 Clashing of tendons ... 74

6 Conclusion ... 77

Reference list ... 79

List of appendices ... 81

List of figures

Fig. 2.1 Flat slab ... 3

Fig. 2.2 Flat slab with column heads and drop panels ... 3

Fig. 2.3 Load-bearing on a strip of flat slab in one direction ... 4

Fig. 2.4 Reduction in building height due to reduction of slab thickness ... 5

Fig. 2.5 Procedure of bonded post-tensioning ... 6

Fig. 2.6 Bonded tendon with multiple 7-wire strands ... 6

Fig. 2.7 Unbonded tendon with a 7-wire strand ... 6

Fig. 2.8 Live end anchorage for a BBR VT CONA Single system ... 7

Fig. 2.9 Dead end anchorage for a BBR VT CONA Single system ... 8

Fig. 2.10 Equivalent forces of a parabola shaped cable ... 8

Fig. 2.11 Idealized parabolic model with equivalent forces ... 9

Fig. 2.12 Realistic parabolic model with equivalent forces ... 9

Fig. 2.13 Distribution of shear forces in an edge-supported slab ... 10

Fig. 2.14 Different tendon layouts ... 11

Fig. 2.15 Span-to-depth ratio for initial determination ... 19

Fig. 2.16 Reduction of span-to-depth ratio due to increased loads ... 20

Fig. 2.17 Minimum clear spacing between ducts ... 21

Fig. 2.18 Spacing of anchorages for the BBR VT CONA Single 0,62” system ... 22

Fig. 2.19 Spacing of anchorages for the BBR VT CONA Single 0,62” system ... 22

Fig. 2.20 Division of panels in flat slabs ... 23

Fig. 2.21 Design strips for bending moments in a finite element analysis ... 24

Fig. 2.22 Illustration of total design bending moment ... 26

Fig. 2.23 Idealized punching shear failure ... 29

Fig. 2.24 Typical basic control perimeters ... 29

Fig. 2.25 Concrete stresses at transfer ... 34

Fig. 2.26 Recommended values of maximum crack width 34
Fig. 2.27 Maximum bar diameters for crack control 35
Fig. 2.28 Maximum bar spacing for crack control 35
Fig. 3.1 Flat slab plan view 38
Fig. 3.2 Flat slab 3D view 38
Fig. 4.1 Flat slab for validation of and comparison of FEM-results [in m] 39
Fig. 4.2 Physical 3D-model in FEM-Design 41
Fig. 4.3 Tendon layout in FEM-Design 41
Fig. 4.4 Tendon profile y-direction in FEM-Design 41
Fig. 4.5 Tendon profile x-direction in FEM-Design 42
Fig. 4.6 Physical 3D-model in ADAPT 42
Fig. 4.7 Tendon layout in ADAPT 42
Fig. 4.8 Tendon profile y-direction in ADAPT 43
Fig. 4.9 Tendon profile x-direction in ADAPT 43
Fig. 4.10 Stress function with all losses included – Hand calculation, y-direction 45
Fig. 4.11 Stress function with all losses included – FEM Design, y-direction 46
Fig. 4.12 Stress function with all losses included – Hand calculation, x-direction 47
Fig. 4.13 Stress function with all losses included – FEM-Design, x-direction 47
Fig. 4.14 Stress function with friction losses included – Hand calculation, y-direction 48
Fig. 4.15 Stress function with friction losses included – FEM-Design, y-direction 48
Fig. 4.16 Different number of tendons used in calculations 49
Fig. 4.17 Initial deflections – FEM-Design 51
Fig. 4.18 Initial deflections – ADAPT 51
Fig. 4.19 Quasi-permanent deflections – FEM Design 52
Fig. 4.20 Quasi-Permanent deflections – ADAPT 52
Fig. 4.21 Top fibre stresses at column in x-direction for quasi-permanent load combination. 56

Fig. 4.22 Moment envelope in x-direction - ADAPT 58

Fig. 4.23 Moment envelope in y-direction - ADAPT 58

Fig. 4.24 Hyperstatic moment in x-direction - ADAPT... 59

Fig. 4.25 Hyperstatic moment in y-direction - ADAPT... 59

Fig. 4.26 Bending moments and capacity in x-direction – ADAPT 60

Fig. 4.27 Bending moments and capacity in y-direction - ADAPT 61

Fig. 5.1 Tendon layout A 65

Fig. 5.2 Tendon layout B.. 65

Fig. 5.3 Tendon layout C.. 66

Fig. 5.4 Tendon layout D 66

Fig. 5.5 Tendon layout E... 66

Fig. 5.6 Tendon layout F 67

Fig. 5.7 Equivalent loads for tendon profile in x-direction for 11x6 slab 68

Fig. 5.8 Control points.. 69

Fig. 5.9 Stresses in top fibre in x-direction due to quasi-permanent load combination with prestressing action excluded.. 71

Fig. 5.10 Stresses in top fibre x-direction due to prestressing actions – Tendon layout A 71

Fig. 5.11 Stresses in top fibre x-direction due to prestressing actions – Tendon layout B 71

Fig. 5.12 Stresses in top fibre x-direction due to prestressing actions – Tendon layout C 72

Fig. 5.13 Stresses in top fibre x-direction due to prestressing actions – Tendon layout D 72

Fig. 5.14 Stresses in top fibre x-direction due to prestressing actions – Tendon layout E 72

Fig. 5.15 Clashing of tendons – Tendon layout A 74

Fig. 5.16 Clashing of tendons – Tendon layout B.. 75

Fig. 5.17 Clashing of tendons – Tendon layout C.. 75

Fig. 5.18 Clashing of tendons – Tendon layout D 75

Fig. 5.19 Clashing of tendons – Tendon layout E.. 76

List of tables

Tab. 2.1 Indicative design working life 18

Tab. 2.2 Spacing of anchorages and minimum slab thickness for the BBR VT CONA Single 0,62” system 22

Tab. 2.3 Simplified apportionment of bending moment for a flat slab 23

Tab. 2.4 Stress limitations when using full width in stress calculations 32

Tab. 2.5 Stress limitations when using a finite element analysis with design strips from Fig. 2.21 in stress calculations 33

Tab. 4.1 Losses of prestress in y-direction 45

Tab. 4.2 Losses of prestress in x-direction 46

Tab. 4.3 Presentation of results with hand calculations based on hypothesis 50

Tab. 4.4 Stresses at column for initial load combination 54

Tab. 4.5 Stresses at span for initial load combination 54

Tab. 4.6 Stresses at column for quasi-permanent load combination 55

Tab. 4.7 Stresses at span for quasi-permanent load combination 55

Tab. 4.8 Ultimate bending moments 58

Tab. 4.9 Bending moment capacities and utilizations 60

Tab. 4.10 Shear stresses and resistance with limitation 62

Tab. 4.11 Shear stresses and resistance at column edge without limitation 62

Tab. 5.1 Flat slab parameters 63

Tab. 5.2 Prestressing parameters 64

Tab. 5.3 Tendon layout analysis – Deflections 67

Tab. 5.4 Tendon layout analysis – Stresses in X-direction 69

Tab. 5.5 Tendon layout analysis – Stresses in Y-direction 70

Tab. 5.6 Bending moment utilizations for a column strip/middle strip approach 73

1 Introduction

1.1 Background

Since concrete has low tensile strength, it is normally reinforced with steel bars which carries the tensile loads. For some structures, e.g. thin structures or structures with long spans, the tensile stresses can be large, and reinforced concrete may no longer be a suitable solution due to costs or design requirements. For such cases, the use of prestressed concrete may be a good option. Prestressed concrete enables longer spans, reduced deflection, smaller cross-sections etc.

One of the prestressing systems is the use of unbonded tendons. This is a strand consisting of several wires of high-strength steel, which is covered by grease and encased in a plastic tube to protect against corrosion and reduce the friction. The use of this system began in the United States at the beginning of the 1950´s and has been used in a great extent since when constructing parking garages and floors. In Europe the use of this system started at the beginning of the 1970´s. [1]

Due to deflection requirements, the use of flat slabs with conventional reinforcement are usually limited to a span length of about seven metres. [2] When the span length is longer, or a thinner slab is desired, the use of prestressing may be sufficient because the prestressing effects will counteract the other loads. Tendons can be placed over flat slabs in different layouts, and the most used tendon layout in flat slabs today is to place the tendons concentrated over the columns in one direction and distributed across the whole slab in the other direction.

1.2 Scope of the thesis

In this thesis the effect of the unbonded tendon layout in flat slabs will be analysed. The influence different layouts have on the results will be compared.

Calculations will be executed by hand and by two programs; ADAPT-Floor Pro (ADAPT) and FEM-Design 17 (FEM-Design). Both programs are based on the finite element method. ADAPT is used in a great extent when designing prestressed structures, while the function of modelling unbonded tendons in FEM-Design was new in version 17 released in January 2018. Comparison of the two programs will also be carried out to enlighten differences.

1.3 Method

To compare results from programs and hand calculation, results for one flat slab with one tendon layout was first calculated by the different methods. The aim of this was to find differences between the programs, but also to validate the results from the programs to avoid a large amount of hand calculations for the further tendon layouts and flat slabs.

To investigate the influence tendon layouts has on flat slabs, three different slabs was defined with three spans in one direction, and two in the other. Span lengths, slab thickness and other parameters was chosen for each slab. Calculations for each slab was carried out regarding five different tendon layouts in addition to one without any tendons. For each slab, the total prestress, tendon profiles and other parameters was the same, the only varying parameter was the placing and distribution of the tendons. The results in terms of deflections, stresses and bending moment among others was then analysed and compared.

2 Theory

2.1 Flat slabs

A flat slab is a slab which is supported by columns without beams between the columns, normally arranged in a rectangular pattern. [3] Such slabs are suitable if large areas without load-bearing walls are desired. This way one can build walls that are not a part of the load-bearing construction, which gives freedom due to prospective needs of changing. [2]

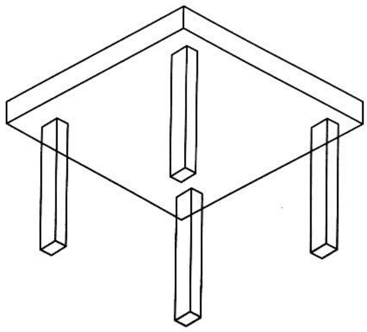


Fig. 2.1 Flat slab [4]

To avoid thick slabs and a large amount of reinforcement, it is recommended to limit the span of a conventional reinforced flat slab to about 7,2 metres. There is no problems building longer spans due to strength requirements, but large deflections often restricts the design. [2] Also the shear forces over the columns tends to be large for flat slabs. A way of increasing the strength of the columns and construct longer spans is to use column heads or drop panels as illustrated in Fig. 2.2. [4]

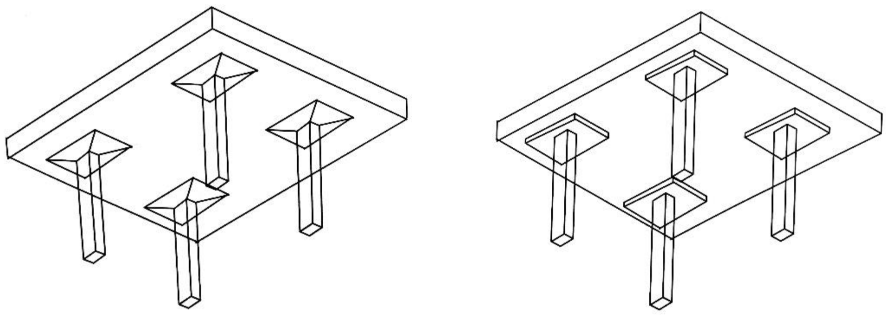


Fig. 2.2 Flat slab with column heads and drop panels [4]

The static behaviour of a flat slab can be imagined as a system of crossing beams, where the beams has the height of the slab thickness, and width equal to half the span to both sides. As illustrated in Fig. 2.3, the total load on the imagined beam is acting in the x-direction. Similarly, the total load is carried by the imagined beams in the y-direction. [3]

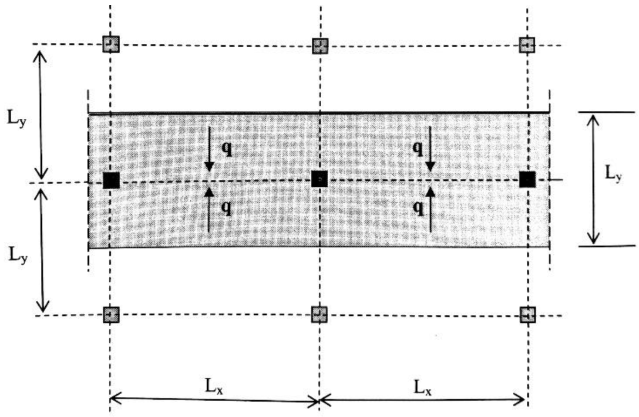


Fig. 2.3 Load-bearing on a strip of flat slab in one direction [3]

2.2 Prestressed concrete

Prestressed concrete is concrete where a compressive stress is applied to counteract the action of forces to a certain extent. A tension force is applied to tendons placed inside the concrete. This force is transferred as compression to the concrete by anchorages or by grip between the tendons and the concrete. By giving the tendons a suitable stress, and placing them appropriate, tensile stresses can be avoided, or greatly reduced. [3]

Compared to conventional reinforced concrete, prestressed concrete has many advantages. Reinforced concrete can crack due to tensile stresses, and this causes several issues: [4]

- The reinforcement is more exposed to corrosion.
- Cracked concrete is less stiff and leads to a larger deflection.
- The shear strength is reduced.
- Cracked concrete does not contribute to carry loads, but it still adds weight to the structure.

Prestressed concrete can, if designed properly, counteract the cracks due to tensile stresses, and hence, the issues with reinforced concrete can be solved partially or completely. The use of prestressed concrete can e.g. increase the length of spans, reduce the number of required columns, reduce the slab thickness, and hence reduce the total building height as shown in Fig. 2.4.

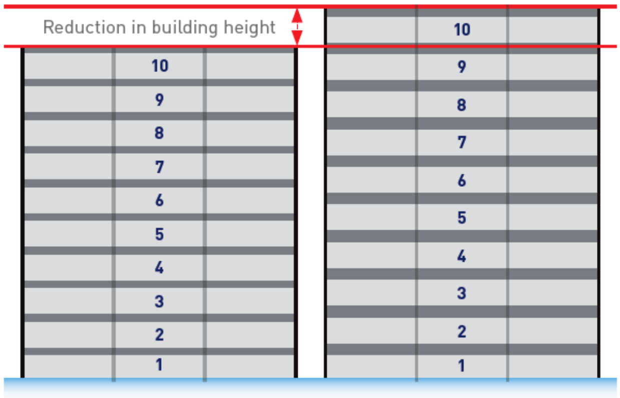


Fig. 2.4 Reduction in building height due to reduction of slab thickness [5]

2.2.1 Post-tensioning

Post-tensioning is a way of pre-stressing concrete, where the tendons are stressed after the concrete is casted. The advantage of post-tensioning is that the tendon profile can be adjusted to the applied load by curves, as opposed to pre-tensioned tendons which has to be straight due to the cables being stretched before the concrete is casted. [6] This makes post-tensioning suitable for structures with multiple spans, where tensile stresses vary between top and bottom fibres of the cross-section. Post-tensioning can be done bonded or unbonded. The procedure of bonded post-tensioning is shown in Fig. 2.5 and is as follows: [3, 6]

a. The formwork of the structure is made, reinforcement and hollow ducts with room for the prestressing steel is placed. Concrete is casted. The hollow ducts are encased in the concrete. Tendons can be put inside the ducts either before or after casting.
b. When the concrete is strong enough, the tendons are tensioned by jacking in one or both ends, and the ends are anchored.
c. After jacking, grout is injected to the ducts.

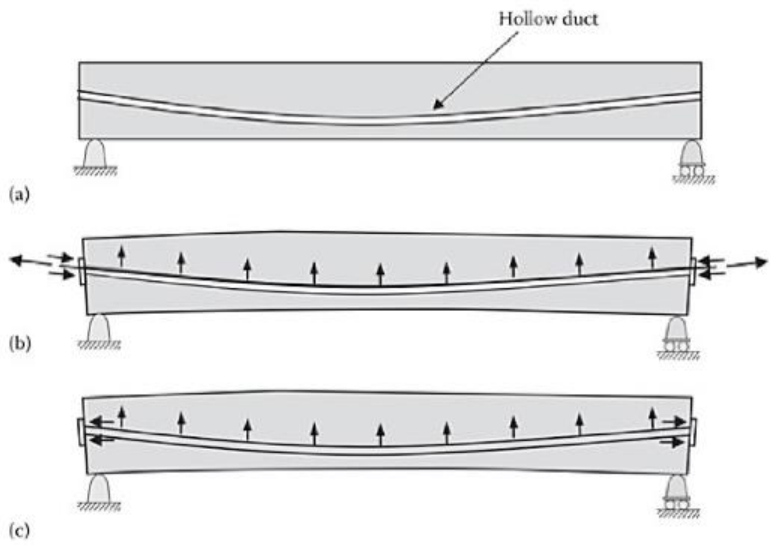


Fig. 2.5 Procedure of bonded post-tensioning [6]

For an unbonded system, the tendons are not laid in hollow ducts and filled with grout. They are encased in plastic tubes with grease and placed before the concrete is casted. Fig. 2.6 and Fig. 2.7 shows illustrations of cross sections of a bonded and an unbonded prestressing tendon.

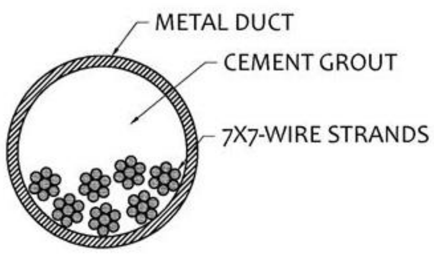


Fig. 2.6 Bonded tendon with multiple 7-wire strands [7]

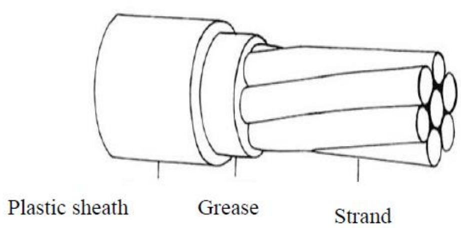


Fig. 2.7 Unbonded tendon with a 7-wire strand [4]

Both systems have their advantages and disadvantages, and the most suitable system is chosen based on the design and requirements of the structure, in addition to costs, availability, experience and so on. [8]

Advantages of the two systems are: [3, 4, 8]

Bonded post-tensioning:

- The prestressing steel can be fully utilized.
- Better cracking behaviour.
- Can have a flat duct system to allow maximum eccentricity.
- Can have multistrand system to transfer large forces.
- Increases the punching shear resistance considerable

Unbonded post-tensioning:

- Simple design and no grouting. Less time to construct.
- Small friction at time of stressing. Reduces losses of prestressing force.
- Protected against corrosion.
- Possible to replace or re-stress the tendons.
- Allows maximum eccentricity.

The unbonded tendons are connected to live end- and dead end anchorages. Jacking is done at live ends. Fig. 2.8 and Fig. 2.9 illustrates a live end anchorage and a dead end anchorage. The anchorages are in principle the same, but the dead end anchorage is delivered ready mounted on the tendons. Due to jacking of the live end, 70cm of the tendon should stand out of the anchorage.

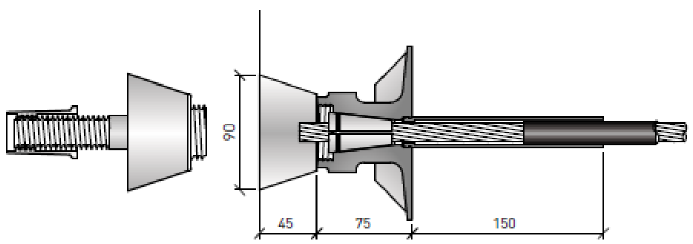


Fig. 2.8 Live end anchorage for a BBR VT CONA Single system [1]

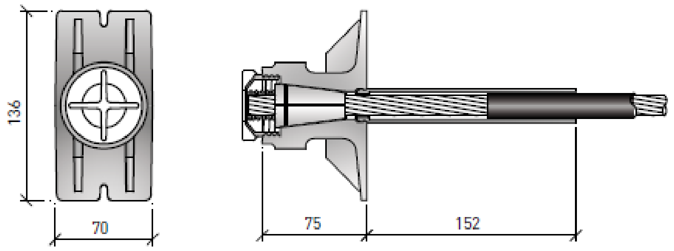


Fig. 2.9 Dead end anchorage for a BBR VT CONA Single system [1]

2.2.2 Load balancing

Load balancing is a method of finding a suitable prestress and cable profile for a given load. The prestressing forces acting on the concrete are called equivalent forces. For a parabola shaped cable profile, the equivalent forces are shown in Fig. 2.10.

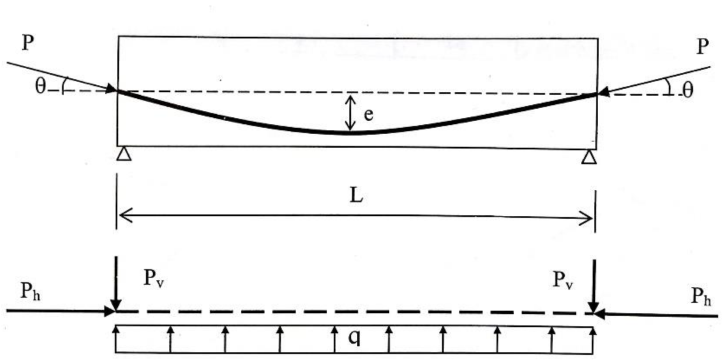


Fig. 2.10 Equivalent forces of a parabola shaped cable [3]

The curvature of the cable gives a uniform load upwards and is therefore suitable for balancing uniform loads. The uniform load, q, is calculated from:

Eq. 2.1 $$q = \frac{8Pe}{L^2}$$

If e.g. the dead load is to be balanced, it is set equal to q, and the required prestressing force, P, can be calculated for a given drape, e, and span length, L. For a perfect load balancing the equivalent force will zero out the dead load, and only the end forces will remain, leaving the cross-section with no deflections and a constant compressive stress. [3]

2.2.2.1 Idealized parabolic model

For a continuous beam over multiple spans, there are tensile stresses in top fibres over the supports. The tendons are placed above the centroid of the beam over the supports (in tensile zones) and forms one parabola for each span. For an idealized model, the profile of the parabolas and the resulting equivalent forces is illustrated in Fig. 2.11.

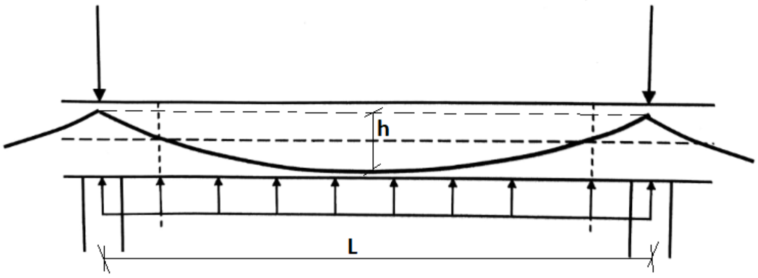


Fig. 2.11 Idealized parabolic model with equivalent forces [3]

The difference from the example in Fig. 2.10 is that the parabola does not have the ends at the centroid. The uniform equivalent load q is calculated from:

Eq. 2.2 $$q = \frac{8Ph}{L^2}$$

Where h is the drape as shown in Fig. 2.11.

2.2.2.2 Realistic parabolic model

The curvature of an idealized model is not possible to achieve due to the buckling of the tendon at support. A more realistic model is shown in Fig. 2.12.

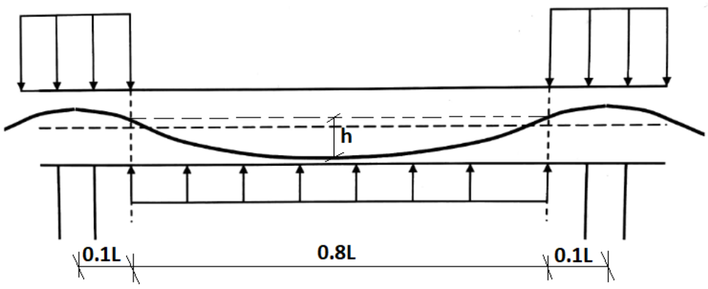


Fig. 2.12 Realistic parabolic model with equivalent forces [3]

The curvature is smoother over the supports, but since there is inflection points on both sides of the supports, parabolas is created over them, and the resulting equivalent force over the support is in the opposite direction. The equivalent forces are calculated using Eq. 2.2, but the length, L, is from inflection point to inflection point, meaning that the drape, h, also will change. The results from the two models will differ, but the idealized model is often used to simplify the calculations.

2.2.2.3 Load balancing of flat slabs

For a two-way edge supported slab, the edges are supported by beams or walls on all sides. For such a slab, the load will be distributed via the beams/walls to the columns, as illustrated in Fig. 2.13. The load balancing is achieved by placing tendons in the span. The tendons can be distributed arbitrarily between x- and y-direction, but together they must balance the desired load. Altogether, twice the desired load is balanced, half by tendons and half by beams/walls. [6]

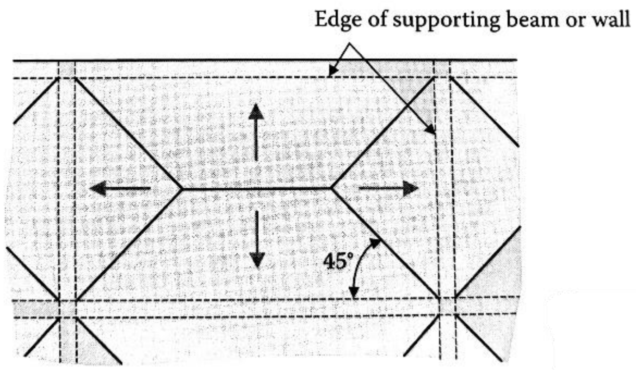


Fig. 2.13 Distribution of shear forces in an edge-supported slab [6]

Flat slabs behave in the same way, only that the load-bearing beams/walls is strips of slab. Since these strips have the same thickness as the slab, it is usually less stiff and more exposed to serviceability problems. The load distribution is about the same. To make the edges stiffer, tendons are placed over the columns. These must carry the same load as the beams/walls for a two-way edge supported slab, i.e. the entire load to be balanced. The further calculation is similar as for a two-way edge supported slab. Altogether, twice the desired load must be balanced, half by column line tendons, and half by slab tendons. [6]

There are several possible arrangements of the tendons, where some is easier to execute, and some makes a better load balancing than others. Ideally the tendons should be distributed between the column lines and the span the same way as the moment is distributed. [2] Some examples of possible tendon layouts are illustrated in Fig. 2.14.

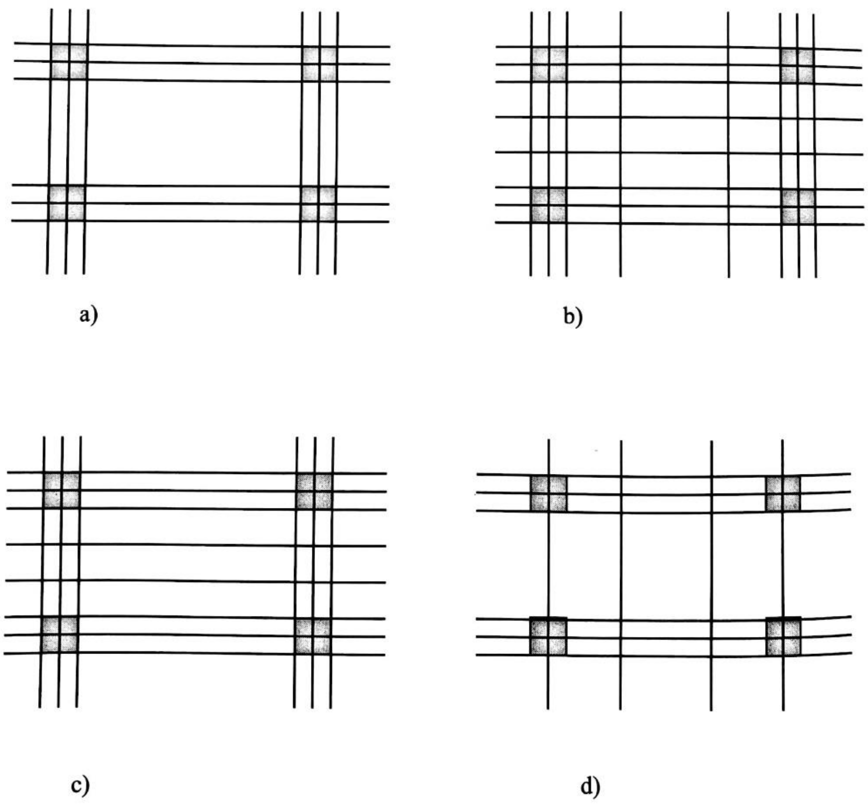


Fig. 2.14 Different tendon layouts [3]

a. Tendons only in column lines.
   - Easy to execute, but no tendons in middle strips indicates that it does not result in the best load balancing.
b. Tendons placed in column lines and in middle strips in both directions.
   - The layout which is most fitted to elasticity theory and is likely to perform best. It is difficult to execute because of weaving of tendons in spans. [3]
c. Tendons in middle strips in direction with longest span only.
   - Avoids weaving of tendons in spans.
d. Tendons in middle strips in one direction, and in column lines the other direction.
   - The weaving of tendons is minimized, and the execution is simplified. [4]
   - Looked upon as a one-way plate with column line tendons as supports. [6]

For slabs, normally 60 – 80% of the dead load is balanced, and for beams, often 80 – 110% of the dead load is balanced. It is suggested to have an average effective prestressing due to the gross sections between 0,85 and 2,0 MPa for flat slabs. The minimum value is according to requirements from the American code; ACI 318-02, and the maximum value is suggested to obtain an economically design. [9, 10]

2.2.3 Prestressing force

2.2.3.1 Maximum stressing force

Clause 5.10.2.1(1)P of Eurocode 2, NS-EN 1992-1-1 (EC2-1-1) gives the restriction of the force applied to a tendon, P_{max}, as: [11]

Eq. 2.3
$$P_{max} = A_p * \sigma_{p,max}$$

where:

A_p	is the cross-sectional area of the tendon
$\sigma_{p,max}$	is the maximum stress applied to the tendon

Eq. 2.4
$$\sigma_{p,max} = \min\{\, k_1 * f_{pk};\ k_2 * f_{p0,1k}\}$$

where:

f_{pk}	is the characteristic tensile strength for the prestressing steel
$f_{p0,1k}$	is the characteristic 0,1% proof stress for the prestressing steel
k_1	is a constant of 0,8
k_2	is a constant of 0,9

2.2.3.2 Losses of prestress for post-tensioning

For several reasons, the jacking force will be reduced. The losses of the prestress are due to immediate losses and time dependent losses, where different actions cause the losses. For unbonded, low-relaxation tendons, the total loss will be about 20% of the jacking force. [12]

❖ *Immediate losses*

The immediate losses are due to elastic shortening of the concrete, friction and anchorage set slip. Clause 5.10.3(2) of EC2-1-1 gives the prestressing force after the immediate losses, $P_{m0}(x)$: [11]

Eq. 2.5 $$P_{m0}(x) = P_{max} - \Delta P_i(x)$$

where:

$\Delta P_i(x)$	is the immediate losses

Due to elastic shortening

Because of the compression force from the anchorages to the concrete, the concrete will deform. When tendons are stressed one after another, the compression in the member will increase. The jack automatically compensates for the compression in the concrete, and hence, the first tendon stressed will have the highest loss, and the last tendon stressed has zero loss. [6] The average of the losses is used in calculations. Clause 5.10.5.1(2) of EC2-1-1 gives the mean loss in each tendon due to elastic shortening of the concrete, ΔP_{el}: [11]

Eq. 2.6 $$\Delta P_{el} = A_p * E_p * \sum \left[\frac{j * \Delta\sigma_c(t)}{E_{cm(t)}}\right]$$

where:

$\Delta\sigma_c(t)$	is the variation of stress at the centre of gravity of the tendons applied
j	is a coefficient equal to (n-1)/2n where n is the number of identical tendons successively prestressed. An approximation of j may be taken as 0,5
$E_{cm(t)}$	is the mean elastic modulus of concrete
E_p	is the mean elastic modulus of prestressing steel

Due to friction in the post-tensioned tendons

Because of the compression due to curvature from the prestressing steel to the plastic tube, there will be friction forces. This loss increases gradually with the distance. [6] Clause 5.10.5.2(1) of EC2-1-1 gives an estimation of the losses due to friction, $\Delta P_\mu(x)$: [11]

Eq. 2.7 $$\Delta P_\mu(x) = P_{max}\left(1 - e^{-\mu(\theta + kx)}\right)$$

where:

μ	is the coefficient of friction between the tendon and the tube
θ	is the sum of the angular displacements over a distance x
k	is an unintentional angular displacement for internal tendons
x	is the distance along the tendon from the jacking edge

Due to anchorage set slip

When the tendons are released from the jack, the wedge in the anchorage will move a distance. This causes a loss of prestress which decreases from the anchorage over a length, L_d. The losses at anchorage can be estimated from Eq. 2.8. [6]

Eq. 2.8 $$\Delta P_{sl} = 2 * \beta * L_d$$

where:

β	is the slope of the friction loss line

Eq. 2.9 $$L_d = \sqrt{\frac{\Delta_{slip} * E_p * A_p}{\beta}}$$

where:

Δ_{slip}	is the anchorage slip

- ***Time dependent losses***

Time dependent losses are due to creep and shrinkage in the concrete, and relaxation in the prestressing steel. Clause 5.10.3(4) of EC2-1-1 gives the prestressing force after time dependent losses, $P_{mt}(x)$: [11]

Eq. 2.10 $$P_{mt}(x) = P_{m0}(x) - \Delta P_{c+s+r}(x)$$

where:

$\Delta P_{c+s+r}(x)$	is the total time dependent loss

Clause 5.10.6(2) of EC2-1-1 gives a simplified method of finding the total time dependent loss: [11]

Eq. 2.11
$$\Delta P_{c+s+r}(x) = A_p \frac{\varepsilon_{cs} * E_p + 0{,}8 * \Delta\sigma_{pr} + \frac{E_p}{E_{cm}} * \varphi(t,t_0) * \sigma_{c,QP}}{1 + \frac{E_p}{E_{cm}} * \frac{A_p}{A_c} * \left(1 + \frac{A_c}{I_c} * z_{cp}^2\right)[1 + 0{,}8 * \varphi(t,t_0)]}$$

where:

ε_{cs}	is the shrinkage strain
$\Delta\sigma_{pr}$	is the absolute value of the variation of stress in the tendon due to relaxation of the prestressing steel
$\varphi(t,t_0)$	is the creep coefficient
$\sigma_{c,QP}$	is the stress in the concrete adjacent to the tendons caused by dead load, initial prestress and other permanent actions
A_c	is the area of the concrete section
I_c	is the second moment of area of the concrete section
z_{cp}	is the distance between the centre of gravity of the concrete section and the tendons

Creep

When the concrete is exposed to a load over a long time, it will continue to compress further than the initial compress from when the load was applied. The increase of the deformation is called creep. Creep is expressed by a creep coefficient, $\varphi(t,t_0)$, which depends on the relative humidity of the environment, the dimension of the concrete section, and the composition of the concrete. [3]

Due to shrinkage

Shrinkage is caused by drying out of the concrete. As opposite of creep, it is not dependent on the loading situation. The total shrinkage strain has two contributions; autogenous shrinkage and drying shrinkage. Autogenous shrinkage is developed during the hardening of the concrete, and the drying shrinkage is developed slowly over a long period, when the dry concrete is exposed to dry air. [3]

Due to relaxation

The losses due to relaxation is caused by a reduction of stress in the prestressing steel when it is exposed to a constant strain over a long period. [3] Clause 3.3.2(4)P of EC2-1-1 defines three relaxation classes: [11]

Class 1	wire or strand – ordinary relaxation
Class 2	wire or strand – low relaxation
Class 3	hot rolled and processed bars

In calculations, the losses of relaxation are based on the percentage loss of relaxation 1000 hours after prestressing, and with a mean temperature of 20°C. From this, the final losses due to relaxation is calculated for a time of 500000 hours. [3]

2.2.3.3 Initial prestress force

Clause 5.10.3(2) of EC2-1-1 gives the restriction of the force applied to the concrete immediately after tensioning and anchoring, $P_{m0}(x)$, as: [11]

Eq. 2.12 $$P_{m0}(x) = A_p * \sigma_{pm0}(x)$$

where:

$\sigma_{pm0}(x)$ is the maximum stress in the tendon immediately after tensioning

Eq. 2.13 $$\sigma_{pm0}(x) = \min\{\, k_7 * f_{pk};\ k_8 * f_{p0,1k}\}$$

where:

k_7 is a constant of 0,75

k_8 is a constant of 0,85

This restriction corresponds to a minimum of about 6% immediate losses.

2.3 Analysis and design guidelines for prestressed concrete members with unbonded tendons

For requirements and calculations, Eurocode 2, NS-EN 1992-1-1, is mainly used, but additional literature is also used as supplement. This chapter also contains information about materials and post-tensioning systems which can be useful for design purposes.

2.3.1 Material

2.3.1.1 Concrete

In structures that are prestressed, concrete with a higher strength than usually used for normal reinforced structures is often preferred. The main reason for this is that the concrete is exposed to a larger compression stress due to the prestressing. By increasing the concrete strength, one can decrease the deflections, increase capacities, and hence keep the dimensions to a minimum. Often used strength classes are B35 – B55, but for some occasions also higher strength classes are used. The composition of the concrete is chosen to obtain little creep and shrinkage. This reduces the losses of the prestressing force and deflections for long-term effects. [3, 6]

2.3.1.2 Steel reinforcement

Steel reinforcement is used in prestressed concrete for the same reasons as for conventional reinforced concrete structures; to give strength, ductility and serviceability to the concrete sections. It can be used to increase the tensile strength and ductility in areas where the amount of prestressed steel is not adequate. It can be used for crack control at service loads. It is also used in the anchorage zones of the prestressed steel to increase the resistance to the transverse tension and high stresses that occurs. [6]

2.3.1.3 Prestressing steel

The losses of the prestressing force due to creep and shrinkage are largely independent of the strength of the steel. This means that for a conventional reinforcement steel, the losses of the prestressing force are larger than for a high-strength steel in percentage. For a practical design, the loss should be a relatively small amount of the total force, and hence the steel should be able to carry very high stresses. A tensile strength of 1000 – 1900 MPa is normal for modern prestressing steel. [3, 6]

2.3.2 Durability

Clause 4.1(1)P of EC2-1-1 states that "*a durable structure shall meet the requirements of serviceability, strength and stability throughout its design working life, without significant loss of utility or excessive unforeseen maintenance.*" [11] The design working life of a structure should be specified according to clause 2.3 of Eurocode 0, NS-EN 1990 (EC0), as shown in Tab. 2.1.

Design working life category	Indicative design working life (years)	Examples
1	10	Temporary structures
2	10 to 20	Replaceable structural parts, e.g. gantry girders, bearings
3	15 to 30	Agricultural and similar structures
4	50	Building structures and other common structures
5	100	Monumental building structures, bridges, and other civil engineering structures

Tab. 2.1 Indicative design working life [13]

The exposure of the chemical and physical conditions of the structure are accounted for by classifying the environmental conditions according to table 4.1 of EC2-1-1. [11] The risk of corrosion, and the reason why corrosion may occur is essential when deciding the exposure class. To avoid corrosion of the reinforcement, there are minimum requirements for the concrete cover, which is the distance between the concrete surface and the surface of the reinforcement closest to the concrete surface.

Eq. 2.14 $$c_{min} = max\{c_{min,b};\ c_{min,dur} + \Delta c_{dur,\gamma} - \Delta c_{dur,st} - \Delta c_{dur,add}; 10mm\}$$

where:

c_{min}	is the minimum concrete cover
$c_{min,b}$	is the minimum cover due to bond requirement
$c_{min,dur}$	is the minimum cover due to environmental conditions
$\Delta c_{dur,\gamma}$	is the additive safety element
$\Delta c_{dur,st}$	is the reduction of minimum cover for use of stainless steel
$\Delta c_{dur,add}$	is the reduction of minimum cover for use of additional protection

The concrete cover used for dimensioning is a nominal cover, c_{nom}, where an additional value for allowance in design, Δc_{dev}, is added. This value is normally 10 mm. [11]

2.3.3 Initial determination of thickness for post-tensioned flat slabs

The slab thickness must be chosen to have sufficient stiffness due to deflections, and to be durable enough. Fig. 2.15 shows a recommendation from the Post-Tensioning Institute for the design of post-tensioned slabs, dependent on the span length. For flat slabs, the ratio of 45, and the longest span length should be used. [6] Fig. 2.16 shows a suggestion of how the ratio could be reduced due to an increase of the super-imposed load on the structure. The most suitable slab thickness may differ from these recommendations because the ratio depends on many different factors.

Floor system	*Span-to-depth ratio l/h*
Flat plate	45
Flat slab with drop panels	50
One-way slab	48
Edge-supported slab	55
Waffle slab	35
Band beams ($b \approx 3h$)	30

Fig. 2.15 Span-to-depth ratio for initial determination [6]

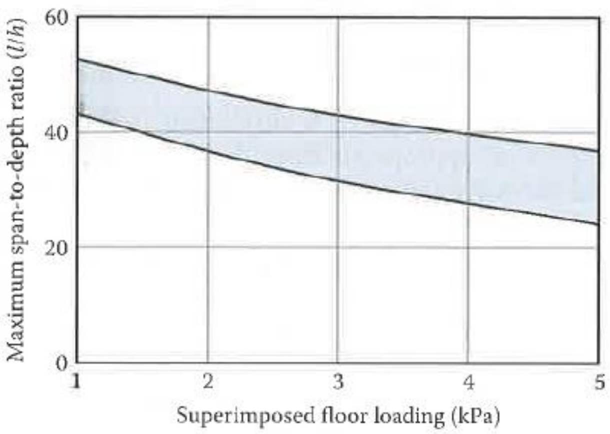


Fig. 2.16 Reduction of span-to-depth ratio due to increased loads [6]

2.3.4 Minimum reinforcement

To prevent brittle failure, wide cracks and resist forces arising from restrained actions, the EC2-1-1 gives regulations of the minimum reinforcement required. The minimum tensile reinforcement, $A_{s,min}$, is given in clause 9.2.1.1(1): [11]

Eq. 2.15 $$A_{s,min} = max\left\{0{,}26\frac{f_{ctm}}{f_{yk}}b_t d;\ 0{,}0013 b_t d\right\}$$

where:

f_{ctm}	is the tensile strength of the concrete
f_{yk}	is the characteristic strength of the reinforcement
b_t	is the width of the tension zone
d	is the effective depth of the cross-section

The maximum cross-sectional area of reinforcement, $A_{s,max}$ is given by clause 9.2.1.1(3) in EC2-1-1: [11]

Eq. 2.16 $$A_{s,max} = 0{,}04A_c$$

The maximum spacing between bars in a slab, $s_{max,slabs}$, is given by clause 9.3.1.1(3) in EC2-1-1: [11]

- For the principal reinforcement: 3h ≤ 400 mm, where h is the height of the slab
- For the secondary reinforcement: 3,5h ≤ 450mm

In areas with concentrated loads or areas of maximum moment:

- For the principal reinforcement: $2h \leq 250$ mm
- For the secondary reinforcement: $3h \leq 400$mm

Clause 9.4.1(2) of EC2-1-1 states that at interior columns, half of the required reinforcement in top should be placed within 0,125 times the span width to both sides of the columns unless precise calculations are made for the serviceability limit state. [11]

2.3.5 Tendon spacing

The minimum clear spacing between ducts should according to EC2-1-1 clause 8.10.1.3 be in accordance with Fig. 2.17. Since unbonded tendons are not placed inside ducts, the clauses apply only to bonded tendons.

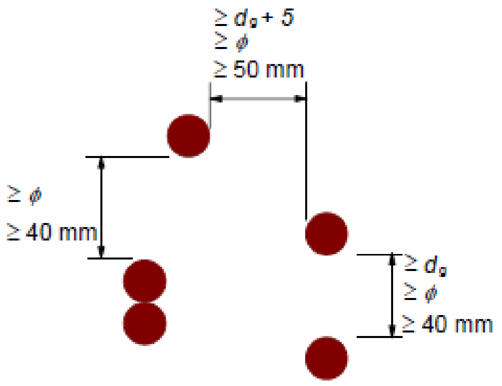


Fig. 2.17 Minimum clear spacing between ducts [11]

Unbonded tendons can be placed in groups of up to four, where the tendons lie next to each other with same heights. The spacing between groups of tendons should be minimum 75mm, or greater than the group width if larger. [14]

At the edges the spacing between anchorages should be in accordance with Fig. 2.18, Fig. 2.19 and Tab. 2.2. These requirements is valid for the BBR VT CONA Single 0,62” system only. [1]

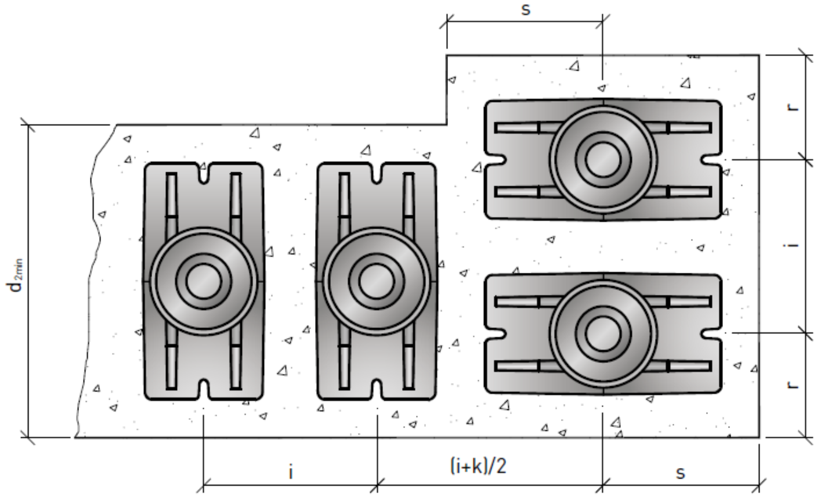


Fig. 2.18 Spacing of anchorages for the BBR VT CONA Single 0,62" system [1]

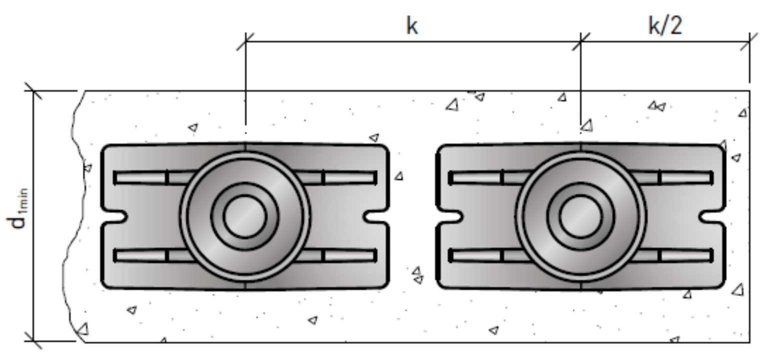


Fig. 2.19 Spacing of anchorages for the BBR VT CONA Single 0,62" system [1]

Concrete strength	c/c spacing		Minimum slab thickness	
f_{ck}	i	k	d_{1min}	d_{2min}
B30	110	170	130	190
B35	110	170	130	190
B45	100	160	120	180
B55	100	160	120	180
B65	100	160	120	180

Tab. 2.2 Spacing of anchorages and minimum slab thickness for the BBR VT CONA Single 0,62" system [1]

2.3.6 Analysis of flat slabs

EC2-1-1 Annex I has information on how flat slabs should be analysed. It states that flat slabs should be analysed using a proven method of analysis such as grillage, finite element, yield line or equivalent frame.

For an equivalent frame analysis, the slab is divided into longitudinally and transversely frames consisting of columns and parts of the slab. The total bending moments from analysis should be distributed across the width of the slab. EC2-1-1 Annex I divides the panels into column- and middle strips, according to Fig. 2.20, and suggests that the total bending moment is distributed according to Tab. 2.3.

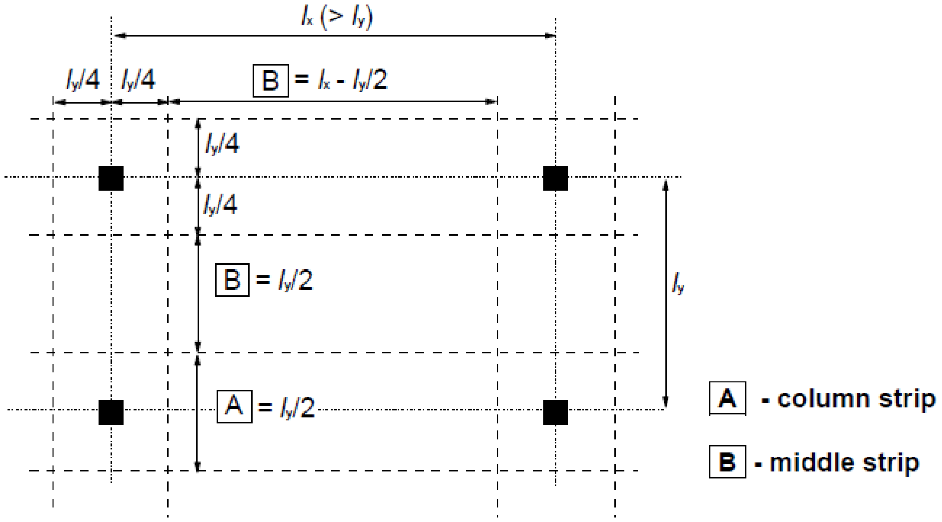


Fig. 2.20 Division of panels in flat slabs [11]

	Negative moments	Positive moments
Column strip	60 – 80 %	50 – 70 %
Middle strip	40 – 20 %	50 – 30 %
NOTE: Total negative and positive moments to be resisted by the middle and column strips together should always add up to 100%		

Tab. 2.3 Simplified apportionment of bending moment for a flat slab [11]

Whenever a flat slab is prestressed, the distribution of the bending moments between column and middle strips are usually not considered. [15] Technical Report No. 43 from the Concrete Society states that *"... due to cracking an averaging of the bending moments across the full panel would normally produce an acceptable solution."* [14]

When using a finite element analysis, design strips can be used according to Fig. 2.21. The bending moments may be averaged across these strips. The width of design strip 2 and 3 is 0,4(w_1+w_2). [14]

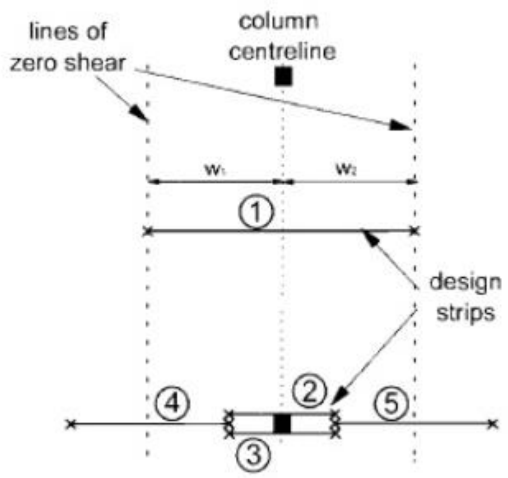


Fig. 2.21 Design strips for bending moments in a finite element analysis [14]

2.3.7 Ultimate Limit State (ULS)

Ultimate limit states are used to avoid collapse of the structure. Equations 6.10a and 6.10b in clause 6.4.3.2 of EC0 contains the load combinations of current interest, where the most disadvantageous one should be used: [13]

Eq. 2.17 $$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\gamma_P P+\gamma_{Q,1}\psi_{0,1}Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i}$$

Eq. 2.18 $$\sum_{j\geq 1}\xi_j\gamma_{G,j}G_{k,j}+\gamma_P P+\gamma_{Q,1}Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i}$$

where:

$G_{k,j}$	is the characteristic value of permanent action j
P	is the representative value of a prestressing action
$Q_{k,i}$	is the characteristic value of a variable action i
$\psi_{0,i}$	is a factor for combination value of a variable action i
ξ_j	is a reduction factor of a variable action j
$\gamma_{G,j}$	is the partial factor of a permanent action j
$\gamma_{Q,i}$	is the partial factor of a variable action i
γ_P	is the partial factor of the prestressing forces

γ_P should be the most disadvantageous of 0,9 and 1,1 according to clause NA.2.4.2.2 of EC2-1-1. In addition, an additional stress, $\Delta\sigma_{p,ULS}$, of 100MPa should be added to the effect of prestressing in ULS calculations given that the tendons is in tension zone in both span and at supports according to clause NA.5.10.8 of EC2-1-1. [11]

2.3.7.1 Bending moment

- ***Design bending moment***

The total design bending moment is the sum of moments due to dead load, live load and the secondary actions in the slab due to the prestressing forces.

Eq. 2.19 $$M_{Ed} = \gamma_g M_{Ek,g} + \gamma_q M_{Ek,q} + \gamma_P M_{Ek,h}$$

where:

$M_{Ek,g}$	is the characteristic moment due to dead load
$M_{Ek,g}$	is the characteristic moment due to live load
$M_{Ek,g}$	is the characteristic hyperstatic moment

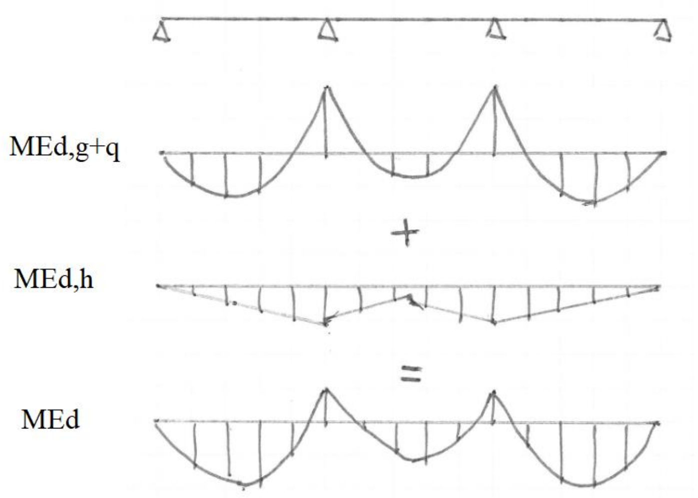


Fig. 2.22 Illustration of total design bending moment

The secondary actions from prestressing causes a hyperstatic moment because the member cannot freely move due to constraint by the supports in statically indeterminate structures. [16] As one can see in Fig. 2.22, the hyperstatic moment will increase the value of the sagging moment in span and decrease the hogging moment at supports.

The hyperstatic moment can be calculated as shown in

Eq. 2.20.

Eq. 2.20 $$M_h = M_p - M_0$$

where:

M_h	is the hyperstatic moment
M_p	is the prestressing moment
M_0	is the primary moment

The prestressing moment is calculated by the equivalent forces from the tendons, and the primary moment is the moment directly caused by the prestressing force and the eccentricity of the tendons. Only the hyperstatic moment is used in the combination of design bending moment, this is because the tendons are not looked upon as forces acting on the member, but internal resistance increasing the bending moment capacity. [3]

- ***Bending moment capacity***

The bending moment capacity calculations are based on lectures in the course Concrete Structures 3 at the Norwegian University of Science and Technology.

The forces in the tendons, S_p, are calculated from:

Eq. 2.21 $$S_p = N(P_{mt} + \Delta\sigma_{p,ULS} * A_p)$$

where:

N	is the number of tendons

The forces in the reinforcement, S_d, are calculated from:

Eq. 2.22 $$S_d = f_{yd} * A_s$$

where:

f_{yd}	is the design strength of the reinforcement
A_s	is the area of the reinforcement

The effective height of the cross section, d_{eff}, is calculated from:

Eq. 2.23 $$d_{eff} = \frac{d_p * s_p + d_d * s_d}{s_p + s_d}$$

where:

d_p is the effective height of the cross section due to the tendons

d_d is the effective height of the cross section due to the reinforcement

The factor, α, is calculated from:

Eq. 2.24 $$\alpha = \frac{s_p + s_d}{0{,}8 * f_{cd} * b * d_{eff}}$$

where:

f_{cd} is the design compression strength of the concrete

b is the width of the section

The bending moment capacity, M_{Rd}, is then calculated from:

Eq. 2.25 $$M_{Rd} = 0{,}8 * \alpha * (1 - 0{,}4\alpha) * b * d_{eff}^2 * f_{cd}$$

Wherever the tendons are distributed across the slab, the capacity is calculated using the whole width of the strip, i.e. the half of the span in each direction from the column centre (like a one-way plate). Where the tendons are banded over columns, the capacity is calculated using the half width of the strip, while the design bending moment comes from the full width of the strip. This will be a conservative approach. [15]

2.3.7.2 Shear

In flat slabs the local shear stresses around the columns can be high and lead to punching shear failure. The failure due to punching shear in a slab/column connection has the form of a cone surrounding the columns, see Fig. 2.23. [4]

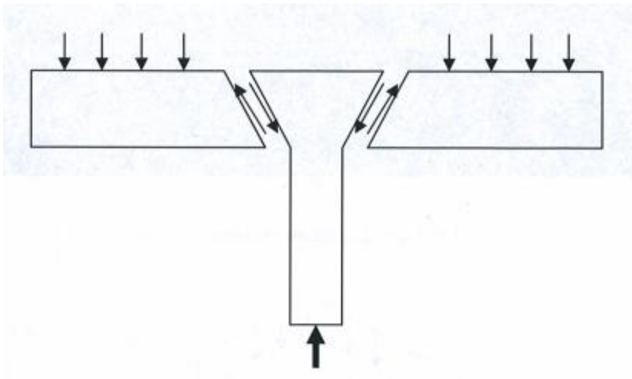


Fig. 2.23 Idealized punching shear failure [4]

A control perimeter, u_1, is defined by Fig. 2.24, where the distance from the edge of the column to the perimeter is two times the effective slab thickness. The effective slab thickness, d_{eff}, can normally be taken as the average of the effective depths of the reinforcement in the two orthogonal directions. [13]

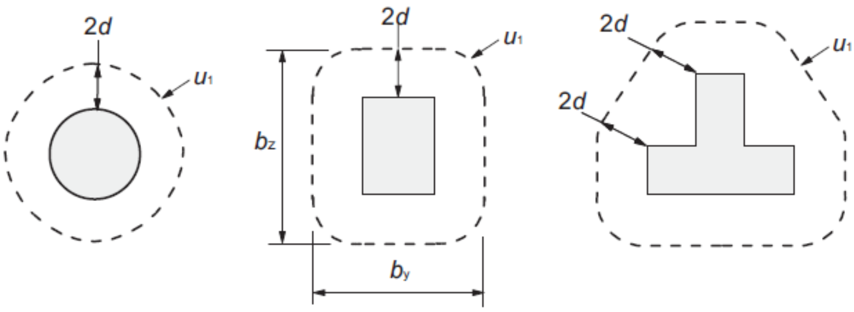


Fig. 2.24 Typical basic control perimeters [13]

The shear stresses, v_{Ed}, is calculated as: [11]

Eq. 2.26 $$v_{Ed} = \beta \frac{V_{Ed}}{u_i * d_{eff}}$$

where:

β	is a factor that consider the unbalanced moment in the column
V_{Ed}	is the shear force (reaction force in the column)
u_i	is the perimeter where the stresses are calculated

EC2-1-1 clause 6.4.3(2) states that shear stresses at the column edge must not exceed $v_{Rd,max}$, and where the shear stresses at the control perimeter exceeds $v_{Rd,c}$, shear reinforcement is needed.

The punching shear resistance, $v_{Rd,c}$ (in MPa), may be calculated as presented in EC2-1-1 clause 6.4.4(1):

Eq. 2.27 $$v_{Rd,c} = max\left[C_{Rd,c}k(100\rho_l f_{ck})^{\frac{1}{3}} + k_1\sigma_{cp};\ \ v_{min} + k_1\sigma_{cp}\right]$$

where:

$C_{Rd,c}$	is a factor of $0{,}18/\gamma_c$
γ_c	is the partial factor of concrete
k	is $min\left[1 + \sqrt{\frac{200}{d_{eff}}}; 2{,}0\right]$ (d_{eff} in mm)
ρ_l	is $min\left[\sqrt{\rho_{ly} * \rho_{lx}}; 0{,}02\right]$
ρ_{ly}, ρ_{lx}	is the reinforcement ratio calculated from the bonded reinforcement in the two directions
f_{ck}	is the characteristic compression strength of concrete
k_1	is a factor of 0,1 when compression and 0,3 when tension
σ_{cp}	is the average of the normal concrete stresses in the two directions
v_{min}	is $0{,}035 * k^{\frac{3}{2}} * f_{ck}^{\frac{1}{2}}$

The maximum punching shear resistance, $v_{Rd,max}$, is calculated as expressed in EC2-1-1 clause NA.6.4.5(3):

Eq. 2.28 $$v_{Rd,max} = 0{,}4 * \nu * f_{cd}$$

where:

ν	is $0{,}6\left(1 - \frac{f_{ck}}{250}\right)$

According to EC2-1-1 clause NA.6.4.5(3) the maximum punching shear resistance should be limited to $1{,}6 * v_{Rd,c} * \frac{u_1}{\beta * u_0}$ where $v_{Rd,c}$ is calculated without the axial stresses ($k_1\sigma_{cp}$=0). The clause also states that this limitation can be ignored if the contribution from concrete (0,75*$v_{Rd,c}$) is ignored in the calculation of the necessary shear reinforcement, see Eq. 2.29.

In slabs with shear reinforcement, the punching shear resistance, $v_{Rd,cs}$, is calculated according to EC2-1-1 clause 6.4.5(1):

Eq. 2.29 $$v_{Rd,cs} = 0{,}75 v_{Rd,c} + 1{,}5 \left(\frac{d_{eff}}{s_r}\right) A_{sw} f_{ywd,ef} \left(\frac{1}{u_1 d_{eff}}\right) \sin\alpha$$

where:

s_r	is the radial spacing of layers of shear reinforcement
A_{sw}	is the area of shear reinforcement in each perimeter
$f_{ywd,ef}$	is effective design strength of the punching shear reinforcement $= 250 + 0{,}25d \le f_{ywd}$
f_{ywd}	is the design yield strength of the shear reinforcement
α	is the angle between the shear reinforcement and the plane of the slab

2.3.8 Serviceability Limit State (SLS)

Serviceability limit states are limit states that affects the function of the structure, the comfort of people and the appearance of the structure. [13] The usual serviceability limit states are: [11]

- Stress limitation
- Crack control
- Deflection control

Clause 6.5.3 of EC0 recommends the use of the quasi-permanent load combination when long-term effects and the appearance of the structure is checked: [13]

Eq. 2.30 $$\sum_{j\geq 1} G_{k,j} + P + \sum_{i\geq 1} \psi_{2,i} Q_{k,i}$$

where:

$\psi_{2,i}$	is a factor for quasi-permanent value of a variable action i

2.3.8.1 Stress limitation

EC2-1-1 has limitations of the stresses in the concrete. The stresses are checked at transfer, when the prestressing force is not affected by the time dependent losses, and under full service loads, where the effect of prestress losses from creep and shrinkage are accounted for. [6]

The compressive stresses are checked to avoid longitudinal cracks. At transfer, the limitation of the compressive stress is $0{,}6f_{ck}$. [6] The initial load combination is the characteristic prestressing force with immediate losses, and the characteristic dead load. Under full service loads, which are the quasi-permanent loads, the limitation of the compressive strength is $0,45f_{ck}$. If the compressive stress exceeds this limit, the effects of non-linear creep should be considered. [11] For this load combination, the characteristic prestressing force with all losses included, and the characteristic dead load plus the permanent part of the live load is used.

Clause 7.1(2) of EC2-1-1 limits the tensile stresses to the concrete tensile strength, f_{ctm}. A larger tensile stress than this limit, indicates that the concrete will have cracks. However, if some minor cracking occurs, reinforcement or tendons near the tensile face will control the cracks. It is important to control the tensile stresses at transfer since areas with compressive stresses under full service loads might be subjected to tensile stresses at transfer. If the concrete cracks at transfer, the cracks might not close completely at service, and it can result in local spalling. [6]

However, when analysing flat slabs, it may be suitable to calculate the stresses looking at the full width of design strips. When calculating the stresses using design sections with the width of half the span to both sides of the columns, the limitations are presented in Tab. 2.4.

		In tension	
Location	**In compression**	With bonded reinforcement	Without bonded reinforcement
Support	$0,3f_{ck}$	$0,9f_{ctm}$	$0,3f_{ctm}$
Span	$0,4f_{ck}$		
Note: Bonded reinforcement may be either bonded tendons or un-tensioned reinforcement			

Tab. 2.4 Stress limitations when using full width in stress calculations [14]

Whenever a finite element analysis with design strips according to Fig. 2.21 is used, the limitations are presented in Tab. 2.5.

		In tension	
Location	**In compression**	With bonded reinforcement	Without bonded reinforcement
Support	$0{,}4f_{ck}$	$1{,}2f_{ctm}$	$0{,}4f_{ctm}$
Span			

Tab. 2.5 Stress limitations when using a finite element analysis with design strips from Fig. 2.21 in stress calculations [14]

The stresses are calculated from Eq. 2.31. It adds the compressive stresses due to prestressing to the bending moments due to the tendon curvatures and other service loads. The effect of the different excitations is added or subtracted depending on the situation and in what fibre the stress is calculated. An illustration of this is shown in Fig. 2.25.

Eq. 2.31 $$\sigma = \frac{P}{A} + \frac{P*e*y}{I} + \frac{M*y}{I}$$

where:

σ	is the stress
P	is the prestressing force
A	is the area of which the prestressing force is acting on
e	is the eccentricity of the tendons
I	is the second moment of area
y	is the distance from the centroidal axis of the section to the fibre
M	is the service moment excluding the moment from the tendons

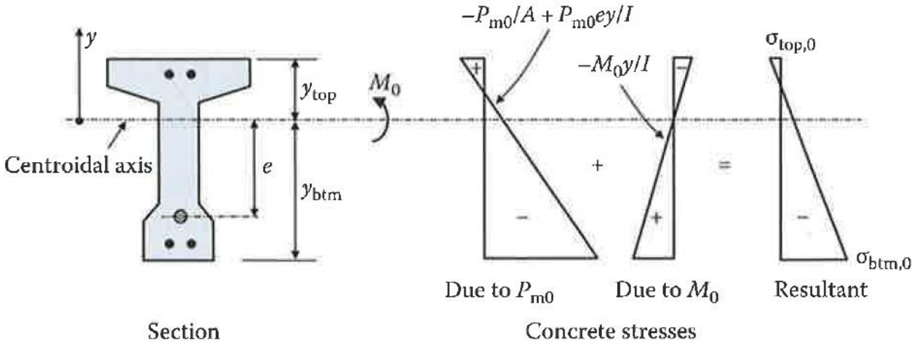


Fig. 2.25 Concrete stresses at transfer [6]

2.3.8.2 Crack control

If the tensile strength of the concrete, f_{ctm}, is exceeded, the concrete will crack. The crack control of flexural cracks in a prestressed slab is in general not critical if there is placed a sufficient amount of reinforcement in the tensile zone. [6] If the concrete cracks, the crack width should be limited to avoid that the function, appearance or durability of the structure is unacceptable. The maximum crack width allowed is given by table 7.1N of EC2-1-1: [11]

<table>
<tr><th>Exposure Class</th><th>Reinforced members and prestressed members with unbonded tendons</th><th>Prestressed members with bonded tendons</th></tr>
<tr><td></td><td>Quasi-permanent load combination</td><td>Frequent load combination</td></tr>
<tr><td>X0, XC1</td><td>0,4[1]</td><td>0,2</td></tr>
<tr><td>XC2, XC3, XC4</td><td rowspan="2">0,3</td><td>0,2[2]</td></tr>
<tr><td>XD1, XD2, XS1, XS2, XS3</td><td>Decompression</td></tr>
<tr><td colspan="3">Note 1: For X0, XC1 exposure classes, crack width has no influence on durability and this limit is set to guarantee acceptable appearance. In the absence of appearance conditions this limit may be relaxed.
Note 2: For these exposure classes, in addition, decompression should be checked under the quasi-permanent combination of loads.</td></tr>
</table>

Fig. 2.26 Recommended values of maximum crack width (mm) [11]

Wherever crack control is required, there are limits for the minimum amount of bonded reinforcement in areas with tension. The calculation of the minimum reinforcement may be as given in clause 7.3.2(2) of EC2-1-1: [11]

Eq. 2.32 $$A_{s,min}\sigma_s = k_c k f_{ct,eff} A_{ct}$$

where:

$A_{s,min}$	is the minimum area of reinforcement within the tensile zone
σ_s	is the maximum stress permitted in the reinforcement
k_c	is a coefficient that accounts for the stress distribution within the section immediately prior to cracking and the change of the lever arm
k	is a coefficient that accounts for the effect of non-uniform self-equilibrating stresses
$f_{ct,eff}$	is the mean value of the tensile strength of the concrete at the time when cracks may first be expected
A_{ct}	is the area of concrete within the tensile zone

To control the crack width, it can be calculated from clause 7.3.4 in EC2-1-1, but it is also possible to do a simpler crack control without calculating the actual crack width. This is done by finding maximum bar diameters and spacing from the following tables due to the steel stress in the cracked section.

Steel stress[2] [MPa]	Maximum bar size [mm]		
	w_k= 0,4 mm	w_k= 0,3 mm	w_k= 0,2 mm
160	40	32	25
200	32	25	16
240	20	16	12
280	16	12	8
320	12	10	6
360	10	8	5
400	8	6	4
450	6	5	-

Fig. 2.27 Maximum bar diameters for crack control [11]

Steel stress[2] [MPa]	Maximum bar spacing [mm]		
	w_k=0,4 mm	w_k=0,3 mm	w_k=0,2 mm
160	300	300	200
200	300	250	150
240	250	200	100
280	200	150	50
320	150	100	-
360	100	50	-

Fig. 2.28 Maximum bar spacing for crack control [11]

2.3.8.3 Deflection control

The deflections due to the quasi-permanent loads should not exceed the limit of L/250, where L is the shortest span of the area to be controlled. Since only the permanent part of the live load is included, it is sufficient to place the live load in every span when calculating the deflections. [11]

3 Determination of conditions

In this thesis, several imaginary flat slabs are being checked. The common denominators for all these slabs are described in this chapter.

3.1 Material

The following materials are used:

Concrete, B35 / B45:

- f_{ck}: 35 / 45 MPa Characteristic compressive strength
- f_{ctm}: 3,2 / 3,8 MPa Mean axial tensile strength
- E_{cm}: 34 / 36 GPa Mean elastic modulus
- α_{cc}: 0,85 Coefficient
- γ_c: 1,5 Partial safety factor
- W_c: 2400kg/m^3 Weight of unreinforced concrete

Reinforcement, B500NC:

- f_{yk}: 500 MPa Characteristic strength
- E_s: 200 GPa Mean elastic modulus
- γ_s: 1,15 Partial safety factor

Prestressing steel, BBR VT CONA Single 0,62” [1]

- A_p: 150 mm^2 Area of tendon
- d_p: 15,7 mm Diameter of tendon
- d_{p2}: 20 mm Diameter of tube surrounding tendons
- f_{pk}: 1860 MPa Nominal strength
- $f_{p0,1k}$: 1670 MPa Nominal yield strength
- γ_p: 1,15 Partial safety factor
- E_p: 196 GPa Mean elastic modulus
- μ: 0,05 Friction coefficient
- k: 0,01 rad/m Wobble coefficient
- Δs: 4 mm Anchorage set slip

3.2 Design

The design of the flat slabs used in this thesis are shown in Fig. 3.1 and Fig. 3.2. The slabs consist of three spans in one direction, and two in the other. The spans in the same direction will have equal lengths. The span lengths, slab thickness, columns, reinforcement and tendons will be changed for different slabs. The flat slab is set to be a part of an office, and the only structural load considered besides the self-weight of the slab, and the loads due to prestressing, is a live load of 3 kN/m^2. The column/slab connection is modelled as hinged.

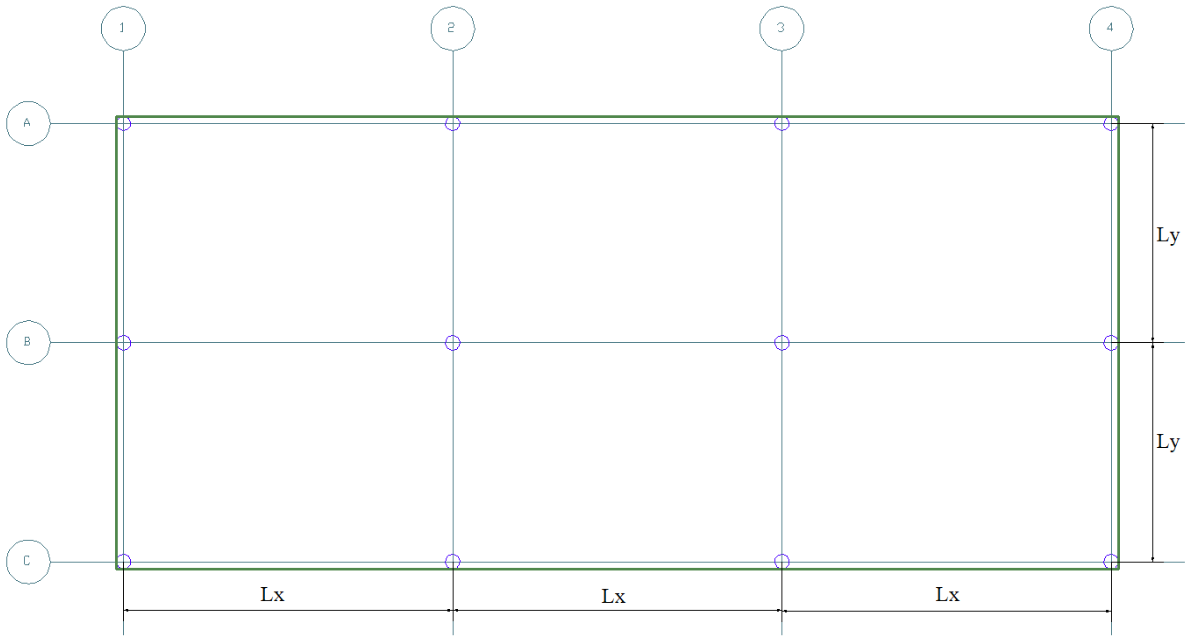


Fig. 3.1 Flat slab plan view

Fig. 3.2 Flat slab 3D view

4 Validation and comparison of FEM-results

To validate the results obtained from the Finite Element Method, the results from the programs; FEM-Design and ADAPT, are being compared with each other, as well as with hand calculations. This is done for one slab with a given tendon layout, and the calculations for this slab are shown in Appendix A - K. Calculations for other slabs will be done similar to this, but they will not be shown in its entirety in appendices.

4.1 Design

The flat slab used for the validation and comparison example is illustrated in Fig. 4.1. It consists of three spans of 9 metres in x-direction, and two spans of 6 metres in y-direction. The slab thickness is set to 200 mm due to the span/thickness factor from chapter 2.3.3. The columns are circular with a diameter of 400 mm. The connections between the slab and the columns are set to be hinged.

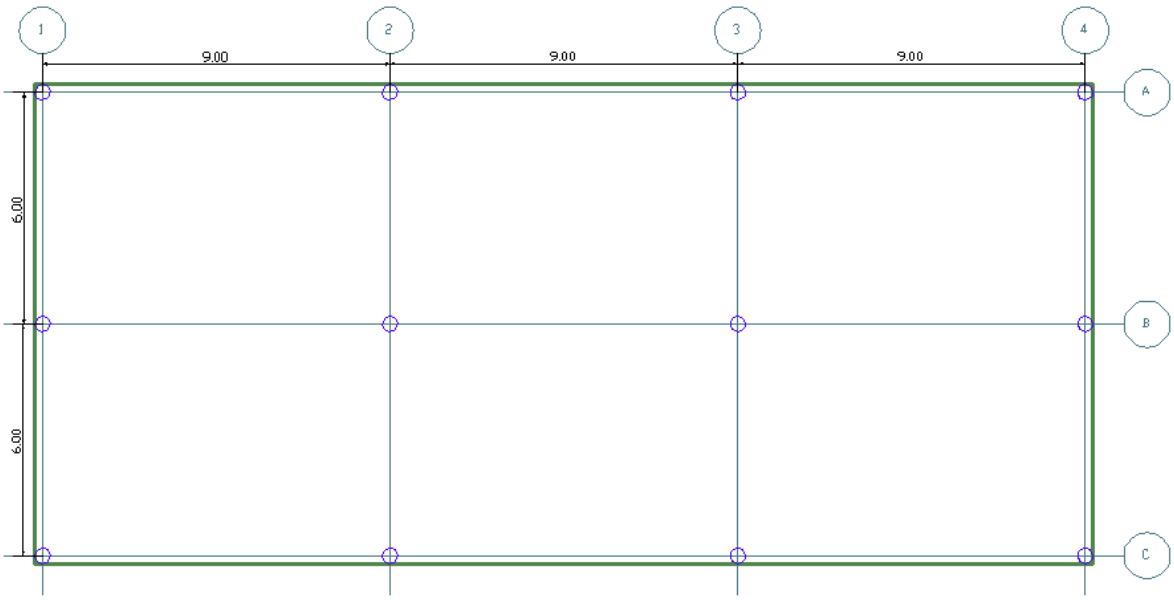


Fig. 4.1 Flat slab for validation of and comparison of FEM-results [in m]

Calculations for cover needed to the reinforcement and tendons, creep and shrinkage coefficients, and minimum reinforcement are shown in Appendix A, B and C.

4.1.1 Load balancing - Tendon layout and profiles

The tendon layout is chosen to be like d) in Fig. 2.14, with concentrated tendons over the columns in the long-span direction (x-direction), and distributed tendons in the short-span direction (y-direction). The tendons will be placed with the same maximum eccentricity over columns and will hence most likely intersect each other in reality. This has not been considered in the further calculations but should be noticed when detailing.

The number of tendons chosen is 24 and 34 in respectively x- and y-direction. This corresponds to an average prestressing of 1,79 MPa and 1,12 MPa, in addition to about 50% and 70% of the dead load balanced due to the idealized parabolic model. The procedure of load balancing is presented in Appendix D.

The layout of the tendons, and the profile of the tendons are shown in illustrations in the following chapters.

4.2 Modelling

The two programs used in this thesis are FEM-Design and ADAPT. FEM-Design is a software for finite element analysis made for the design of concrete structures, but developed to also model, analyse and design steel, timber and foundation structures according to Eurocode with national annexes. [17] The feature of modelling unbonded tendons was new due to January 2018. The feature is for analysis purposes only. FEM-Design converts the tendon profiles into equivalent loads which is used in load combinations for the analysis. The finite element types used in the analysis are fine elements with 9, 6 and 3 nodes for hence square, triangular and line elements.

ADAPT is a three dimensional finite element software made for analysis and design of concrete and post-tensioned floor systems. [18] The software is based on the American code ACI 318, but it also supports the European EC2, but without national annexes. As opposite to FEM-Design, the modelling of tendons is not done as applied loading, but as load resisting elements. This means that the tendons are not “removed” from the concrete member. [19] By default, the finite element types used in the program is flat quadrilateral shell elements. [20]

4.2.1 FEM-Design 17

The full modelling progress is shown in Appendix E.

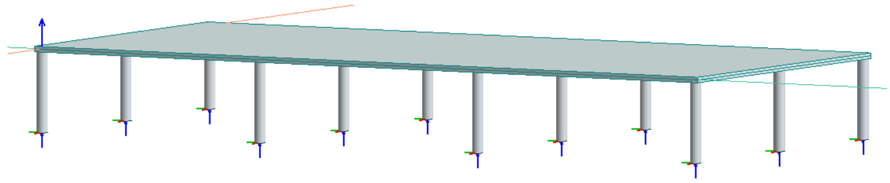


Fig. 4.2 Physical 3D-model in FEM-Design

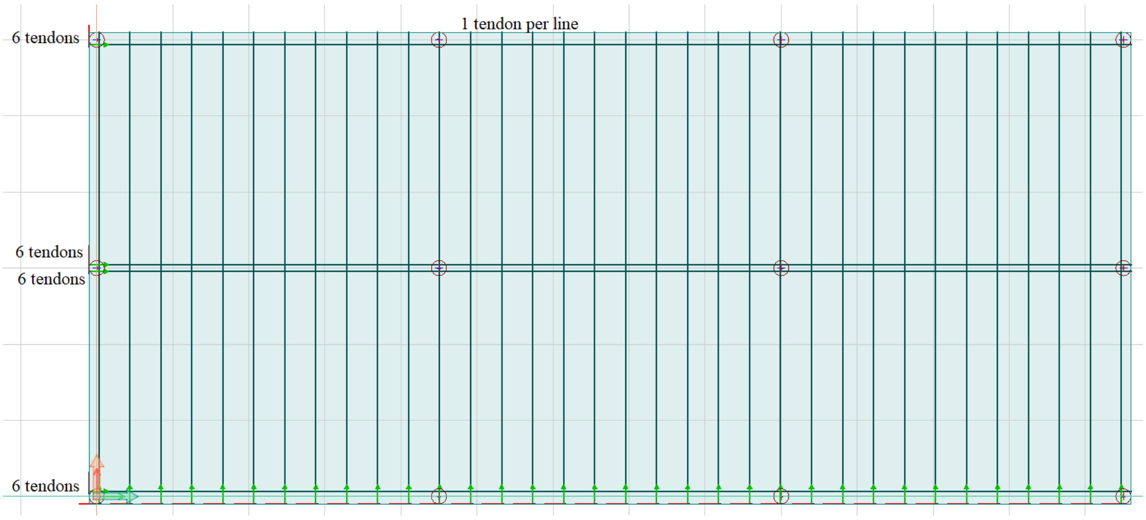


Fig. 4.3 Tendon layout in FEM-Design

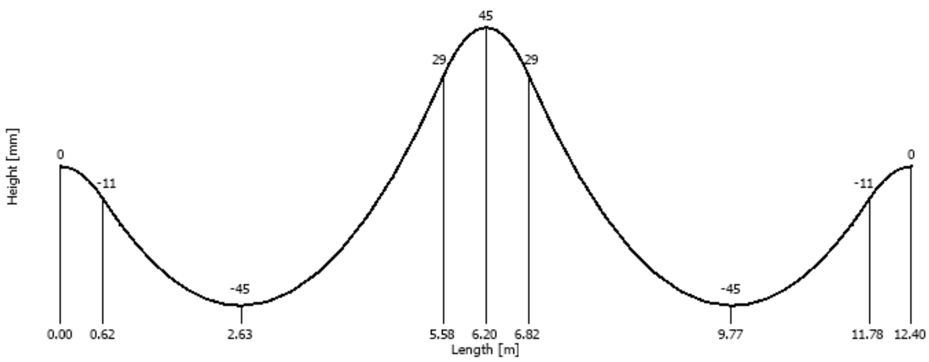


Fig. 4.4 Tendon profile y-direction in FEM-Design

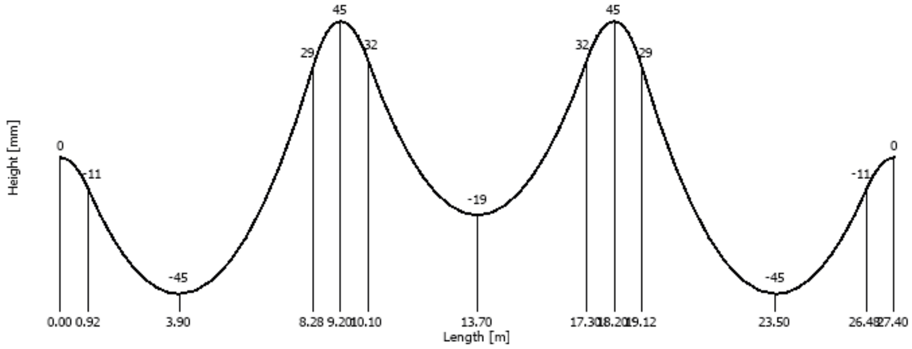


Fig. 4.5 Tendon profile x-direction in FEM-Design

4.2.2 ADAPT-Floor Pro

The full modelling progress is shown in Appendix F.

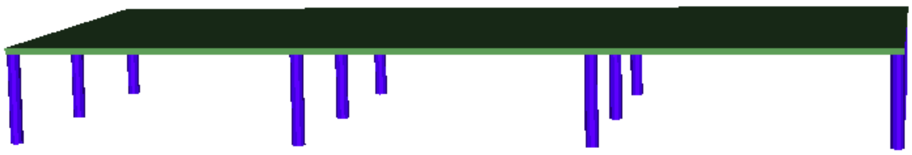


Fig. 4.6 Physical 3D-model in ADAPT

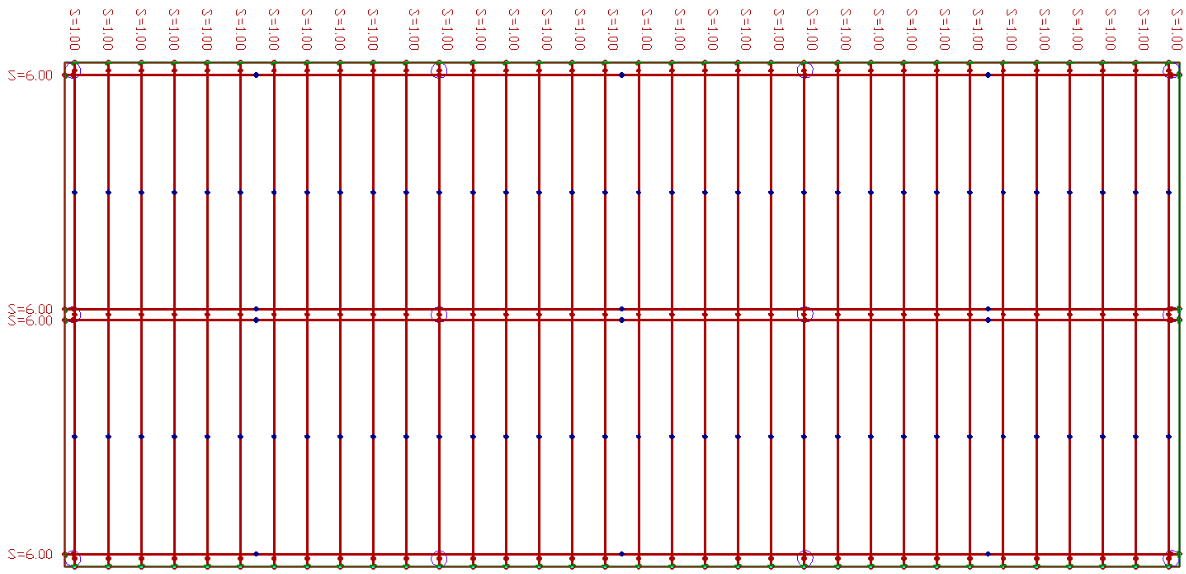


Fig. 4.7 Tendon layout in ADAPT

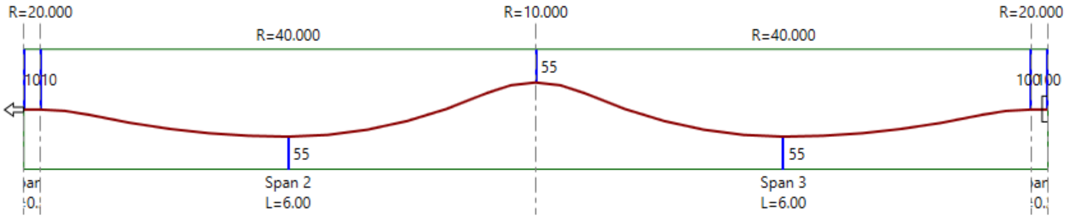


Fig. 4.8 Tendon profile y-direction in ADAPT

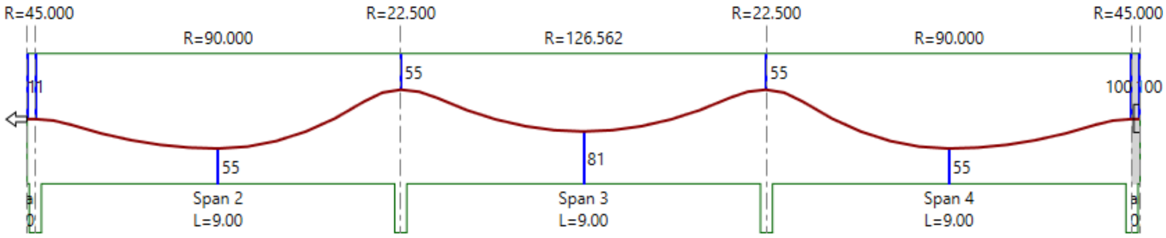


Fig. 4.9 Tendon profile x-direction in ADAPT

4.2.3 Differences in the modelling and analysis process

The main difference between the two programs is that ADAPT can be used to design post-tensioned flat slabs, while FEM-Design uses post-tensioning with unbonded tendons only for analysis purposes. ADAPT uses design sections where the bending moments are averaged across the width, while FEM-Design does not.

Both programs can estimate the initial prestressing losses of the tendons, while only FEM-Design can estimate the long-term losses. In ADAPT the long-term losses are inserted manually. It should be noted that long-term losses can be calculated by another ADAPT software, but this has not been used in this thesis.

There are some differences in load cases they use for the prestressing force. FEM-Design extracts two different load cases, one including only the initial losses of the prestressing force, and one including the total losses. The first one can then be used for the load combination at transfer, while the latter can be used for the quasi-permanent load combination. ADAPT only extracts one load case which includes the total losses of the prestressing force. This is used in both the initial and the quasi-permanent load combination. This should be noted when checking the load combination at transfer, because it will cause a less prestressing force used in calculations than it is.

ADAPT creates a load case called hyperstatic, which results in the hyperstatic bending moment as explained in chapter 2.3.7.1. This load case is added in the strength load combinations and will lead to a reduced hogging moment and an increased sagging moment. FEM-Design does not calculate this moment, and the strength load combinations will hence not be valid.

The effect of creep and shrinkage for long-term deflections are also accounted for differently. FEM-Design uses values as calculated in EC2-1-1, while ADAPT uses a creep and shrinkage factor as given by the American code ACI 318-02. This factor is used to multiply the results from the sustained load combination with 1 + creep and shrinkage factor.

4.3 Losses of prestress

To verify the calculations of the losses of prestress, the distributed tendons in y-direction, and the banded tendons in the interior strip in x-direction is checked. Since the calculation of the losses cannot be viewed in ADAPT, only hand calculations and estimations from FEM-Design are compared. The calculations of both the hand calculations and FEM-Design are based on EC2-1-1 and should resemble each other. Hand calculations are shown in Appendix G and H.

4.3.1 Distributed tendons - Y-direction

The calculated losses are presented in Tab. 4.1, and the resulting stress function from hand calculations and FEM-Design are shown in Fig. 4.10 and Fig. 4.11. Further comments on the results are made in chapter 4.3.3.

Losses of prestress	Hand calculations	FEM-Design
Due to friction (at dead end)	5,1 kN (2,3%)	5,1 kN (2,3%)
Due to anchorage set slip (at live end)	13,9 kN (6,2%)	14,6 kN (6,5%)
Due to elastic shortening	0,9 kN (0,4%)	1,1 kN (0,5%)
Initial losses, ΔP_{m0} (average)	12,0 kN (5,4%)	13,1 kN (5,9%)
Due to creep	0,6 kN (0,3%)	3,3 kN (1,5%)
Due to shrinkage	14,1 kN (6,3%)	14,1 kN (6,3%)
Due to relaxation	8,0 kN (3,6%)	8,1 kN (3,6%)
Total losses, ΔP_{mt} (average)	34,7 kN (15,5%)	38,6 kN (17,3%)

Tab. 4.1 Losses of prestress in y-direction

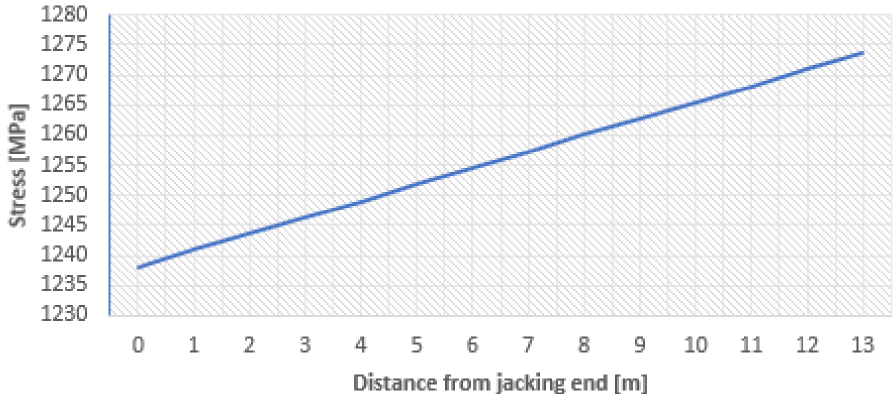


Fig. 4.10 Stress function with all losses included – Hand calculation, y-direction

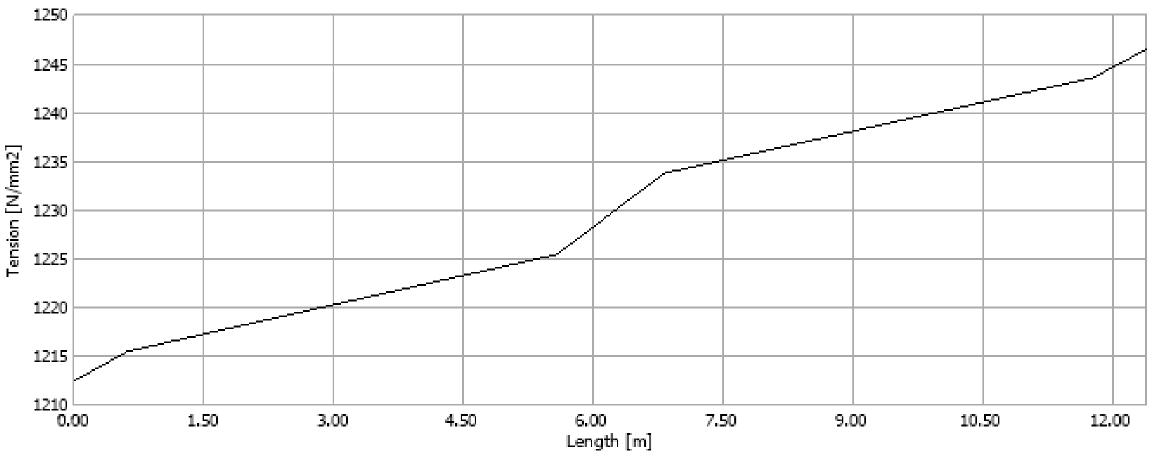


Fig. 4.11 Stress function with all losses included – FEM Design, y-direction

4.3.2 Concentrated tendon - X-direction

The calculated losses are presented in Tab. 4.2, and the resulting stress function from hand calculations and FEM-Design are shown in Fig. 4.12 and Fig. 4.13. Further comments on the results are made in chapter 4.3.3.

Losses of prestress	Hand calculations	FEM-Design
Due to friction (at dead end)	6,8 kN (3,0%)	6,8 kN (3,0%)
Due to anchorage set slip (at live end)	10,8 kN (4,8%)	10,7 kN (4,8%)
Due to elastic shortening	4,3 kN (1,9%)	8,2 kN (3,7%)
Initial losses, ΔP_{m0} (average)	11,8 kN (5,3%)	15,9 kN (7,1%)
Due to creep	12,5 kN (5,6%)	19,5 kN (8,7%)
Due to shrinkage	14,1 kN (6,3%)	14,1 kN (6,3%)
Due to relaxation	8,0 kN (3,6%)	7,7 kN (3,4%)
Total losses, ΔP_{mt} (average)	46,4 kN (20,8%)	57,2 kN (25,6%)

Tab. 4.2 Losses of prestress in x-direction

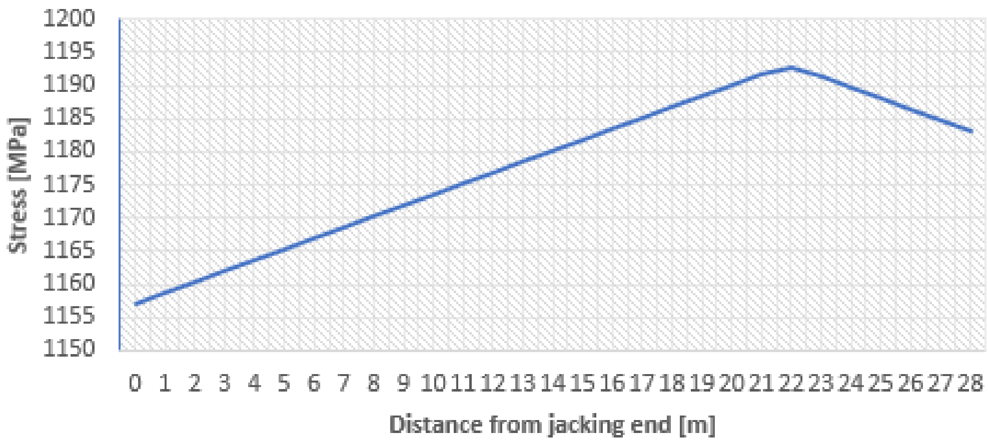


Fig. 4.12 Stress function with all losses included – Hand calculation, x-direction

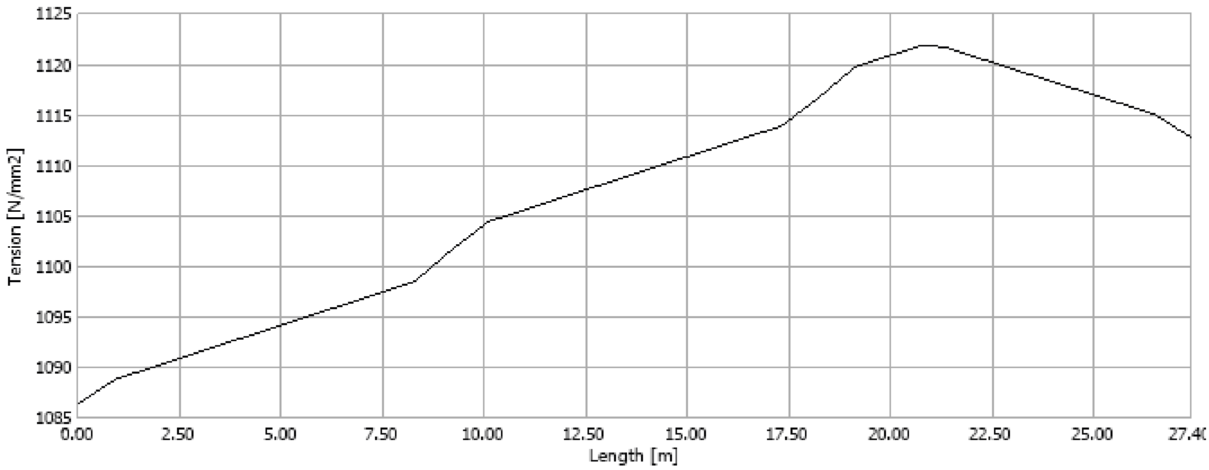


Fig. 4.13 Stress function with all losses included – FEM-Design, x-direction

4.3.3 Discussion

In Tab. 4.1 and Tab. 4.2 one can see that the results due to friction, relaxation and shrinkage corresponds very well. The loss due to anchorage set slip differs a bit in y-direction. The hand calculations are based on a linear loss of prestress due to friction as shown in Fig. 4.14. This is a simplification of the stress function, as the sum of the angular displacement along the tendon does not increase linearly along the tendon. FEM-Design does not use a linear loss line as shown in Fig. 4.15. The slope of the loss line at the anchorage is larger than the average slope, and this will lead to an increased loss of prestress due to the anchorage set slip. Due to this, it is assumed that the estimate of the losses due to anchorage set slip from FEM-Design is more accurate than hand calculations.

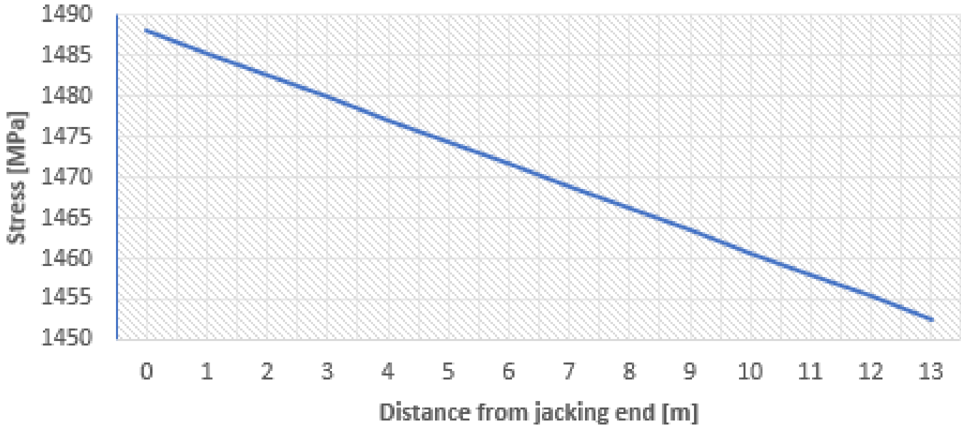


Fig. 4.14 Stress function with friction losses included – Hand calculation, y-direction

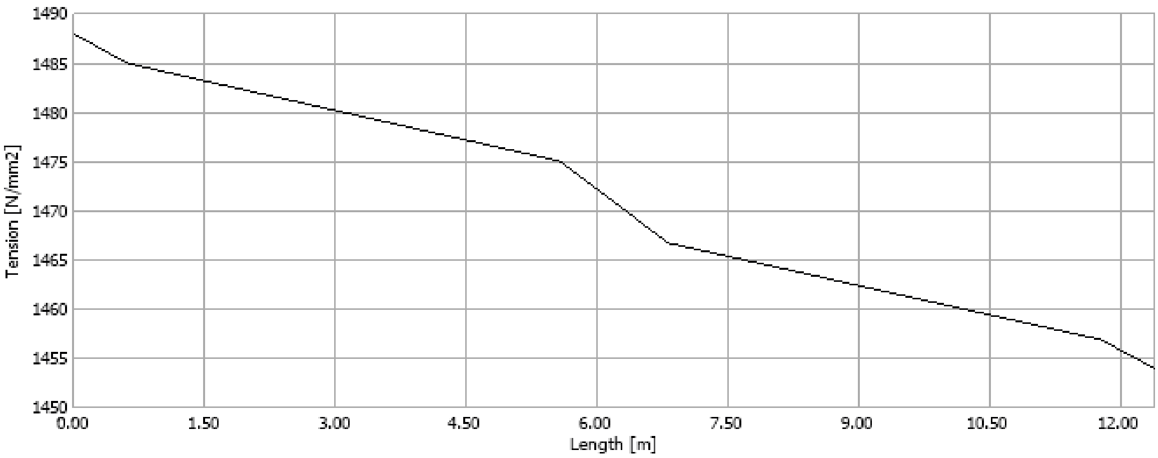


Fig. 4.15 Stress function with friction losses included – FEM-Design, y-direction

The losses due to elastic shortening and creep differs in the two calculations. Further investigation on this shows that the calculation of the stresses, $\Delta\sigma_c$ and $\sigma_{c,QP}$, is likely to be the reason of this. FEM-Design calculates, if the parent object of the tendons is a plate, the stresses based on a 1m strip. For the $\Delta\sigma_c$ calculation, the number of tendons within 1m can be inserted, while it cannot for the $\sigma_{c,QP}$ calculation in the long-term loss estimation. FEM-Design probably uses the inserted number of tendons within a 1m strip for the calculation of $\Delta\sigma_c$, and the number of tendons represented by the current line for the $\sigma_{c,QP}$ calculation. Fig. 4.16 shows the difference of these two number of tendons. It has not been confirmed by the software supplier that this is the case, but the hypothesis is supported by calculations showed in Tab. 4.3.

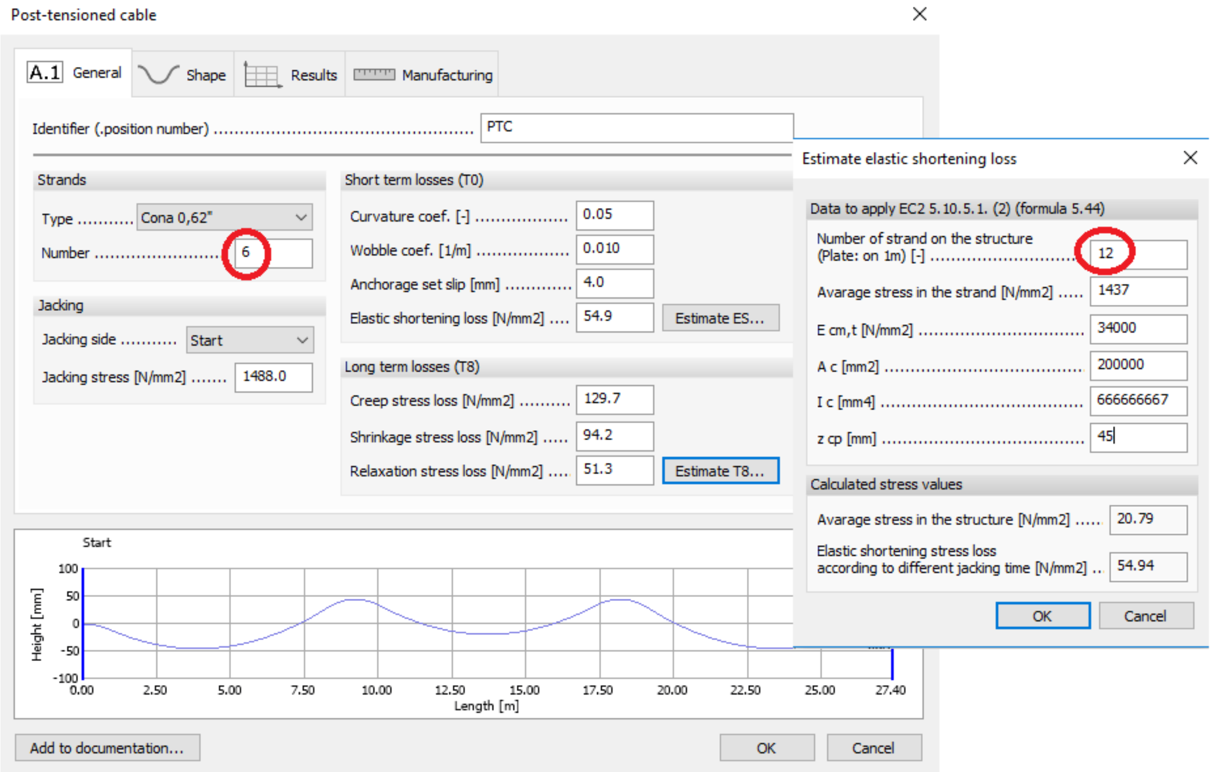


Fig. 4.16 Different number of tendons used in calculations

Also, since the stresses are calculated before the slab is analysed, it is assumed that it does not account for the bending moment due to permanent loads, which would decrease the calculated stress. This is also not confirmed but supported by results presented in Tab. 4.3. The table presents the results the hand calculations would have if they were calculated the way FEM-Design does if my presented hypothesis is used.

		Hand calculations (initial)	FEM-Design	Hand calculations (hypothesis)
Y-direction	$\Delta\sigma_c$	2,11 MPa	2,16 MPa	2,09 MPa
	Losses due to elastic shortening	0,9 kN (0,4%)	1,1 kN (0,5%)	0,9 kN (0,4%)
	$\sigma_{c,QP}$	0,31 MPa	1,69 MPa	1,70 MPa
	Losses due to creep	0,6 kN (0,3%)	3,3 kN (1,5%)	3,2 kN (1,4%)
X-direction	$\Delta\sigma_c$	9,95 MPa	20,79 MPa	20,81 MPa
	Losses due to elastic shortening	4,3 kN (1,9%)	8,2 kN (3,7%)	9,0 kN (4,0%)
	$\sigma_{c,QP}$	6,53 MPa	10,0 MPa	9,97 MPa
	Losses due to creep	12,5 kN (5,6%)	19,5 kN (8,7%)	19,0 kN (8,5%)

Tab. 4.3 Presentation of results with hand calculations based on hypothesis

These results indicate that the hypothesis is completely or partially true. This means that FEM-Design neglects the moments from permanent loads and uses a 1m strip neglecting the influence from tendons idealized by another line in the model that is closer than 1m. In addition, it neglects the fact that the compressive stress at the anchorages will spread out across the width of the slab.

The stresses used in calculations are the stresses at the tendon height above the internal columns. The real stresses will vary both in distance from the anchorages, and at different tendon heights. The average stress will hence be lower than what is used in calculation, and the calculated losses due to creep will be conservative.

Since ADAPT will be used in great extent in the further part of the thesis, and it does not estimate long-term losses itself, a chosen effective force will be used for other models in ADAPT. The effective force is chosen to have a total of 20% losses based on theory from chapter 2.2.3.2 and presented results.

4.4 Deflection

The deflection of the initial and the quasi-permanent load combinations are calculated by the two finite element models.

4.4.1 Initial load combination

The deflections for the initial load combination including the characteristic prestressing actions and dead load are presented in Fig. 4.17 and Fig. 4.18.

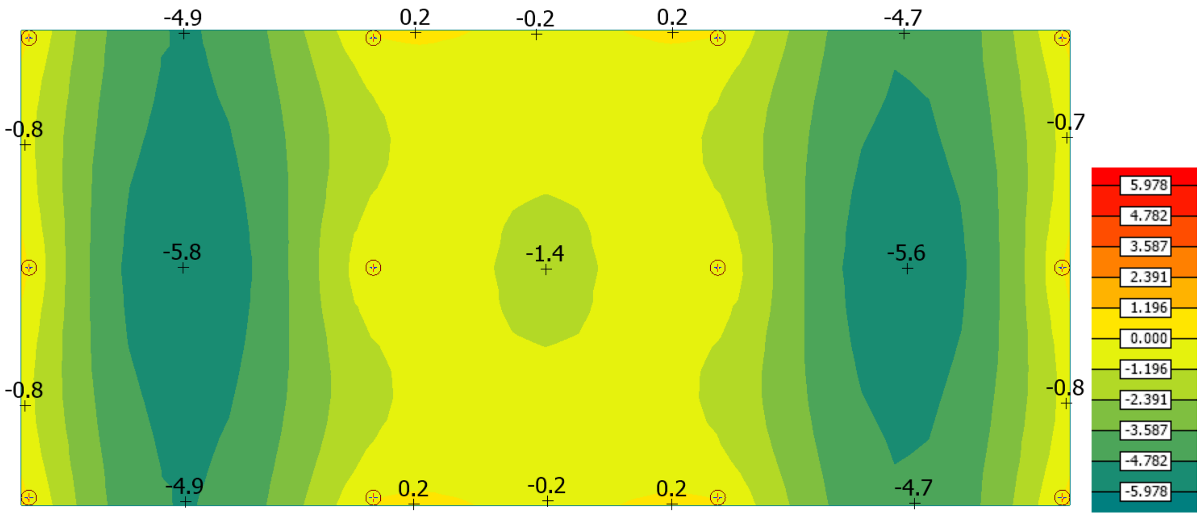


Fig. 4.17 Initial deflections – FEM-Design [mm] (negative values = downward deflections)

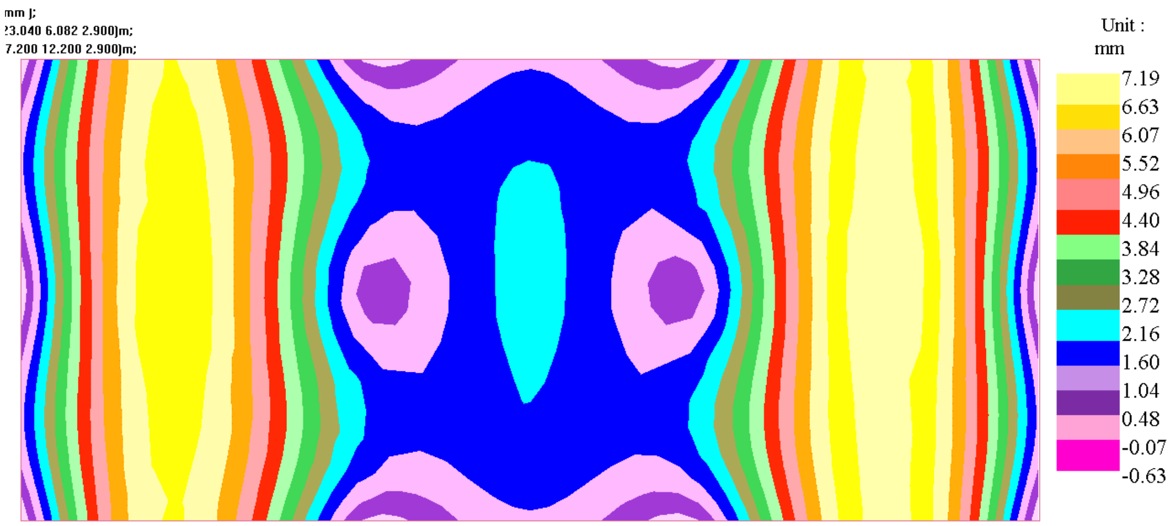


Fig. 4.18 Initial deflections – ADAPT (positive values = downward deflections)

The deflection pattern of the two results is very similar to each other. The maximum deflection is 1,4mm larger in the results from ADAPT. Since ADAPT does not have a load case with only the initial losses of prestress included, ADAPT will use a lower prestressing force in the calculations than FEM-Design. This will lead to a larger deflection. If the deflection in FEM-Design is calculated with all losses included, the maximum deflection is 6,9mm. The difference will then be only 0,3mm, which indicates that the models are quite similar.

4.4.2 Quasi-permanent load combination

The deflections for the quasi-permanent load combination including the characteristic dead load and prestressing actions, permanent part of the live load, and the effects from shrinkage and creep are presented in Fig. 4.19 and Fig. 4.20.

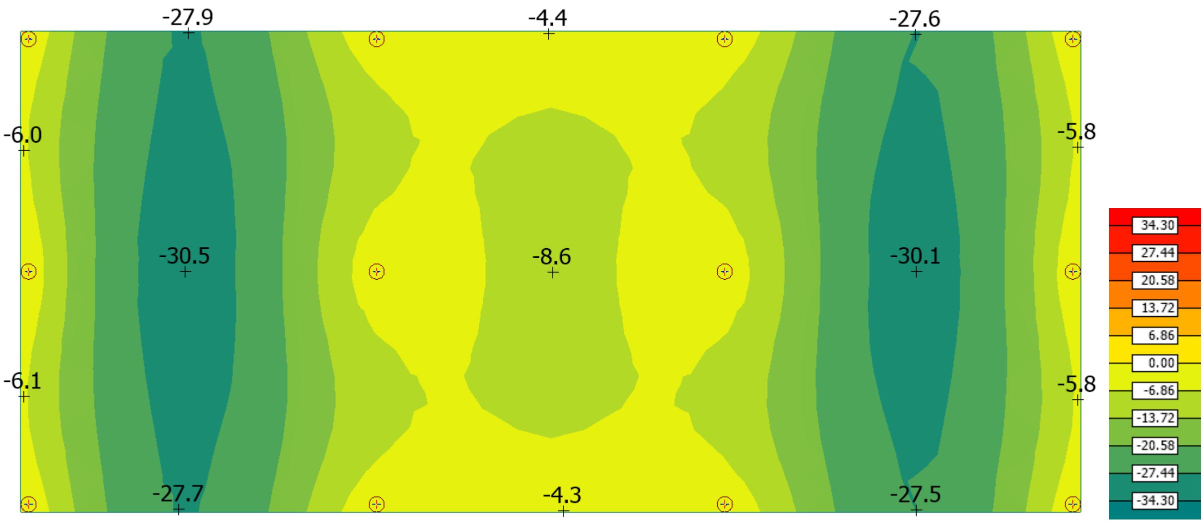


Fig. 4.19 Quasi-permanent deflections – FEM Design [mm] (negative values = downward deflections)

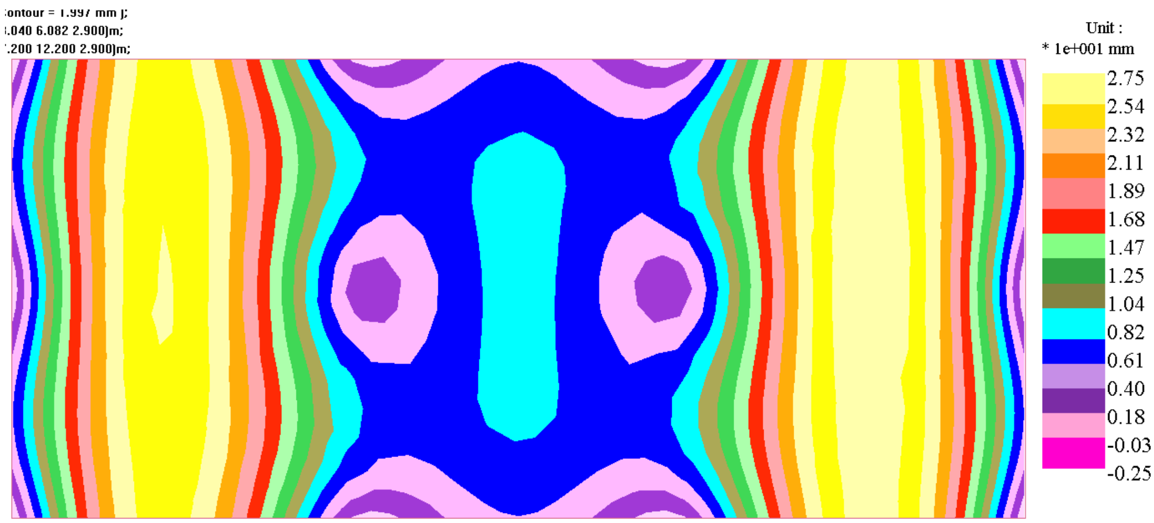


Fig. 4.20 Quasi-Permanent deflections – ADAPT (positive values = downward deflections)

The pattern of the two results corresponds to each other. Maximum deflection in ADAPT is 27,5mm while it is 30,5mm in FEM-Design. The little difference in the two results is likely due to the way shrinkage and creep effects are accounted for, as explained in chapter 4.2.3.

It should be noted that the maximum allowed deflection, L/250 = 24mm, is exceeded in these finite element calculations. The design will hence not be sufficient due to serviceability limit states. To get a sufficient result, several parameters could be changed. A larger amount of prestressing or a thicker slab could be suitable.

4.5 Stresses

The stresses are calculated by hand, in addition to FEM-Design and ADAPT. They are calculated for the initial and quasi-permanent load combination at column and at span. In the x-direction it will be calculated at the exterior span, and not at the interior span. Tensile stresses are represented with positive values. FEM-Design does not use design strips, but the stresses have manually been averaged across the width of design strips according to chapter 2.3.6. It should be noted that hand calculations and ADAPT-calculations are not based on the same design strips as FEM-Design, but on full width design strips. According to chapter 2.3.8.1 they will have different stress limitations, and larger values should hence be expected by the FEM-Design results. Hand calculations are presented in Appendix I.

4.5.1 Initial load combination

The stresses for the initial load combination are presented in Tab. 4.4 and Tab. 4.5. Comments and explanations regarding the differences in the results are presented in the discussion chapter 4.5.3.

		At column		
		Hand calculations	ADAPT	FEM-Design
X-direction	Top fibre stresses	1,11 MPa	2,47 MPa	3,43 MPa
	Bottom fibre stresses	-5,34 MPa	-5,21 MPa	-7,41 MPa
Y-direction	Top fibre stresses	0,25 MPa	0,01 MPa	1,43 MPa
	Bottom fibre stresses	-2,91 MPa	-2,25 MPa	-4,15 MPa

Tab. 4.4 Stresses at column for initial load combination

		At span		
		Hand calculations	ADAPT	FEM-Design
X-direction	Top fibre stresses	-4,12 MPa	-4,53 MPa	-4,09 MPa
	Bottom fibre stresses	-0,11 MPa	2,11 MPa	0,28 MPa
Y-direction	Top fibre stresses	-1,43 MPa	-2,02 MPa	-1,91 MPa
	Bottom fibre stresses	-1,23 MPa	-0,14 MPa	-0,85 MPa

Tab. 4.5 Stresses at span for initial load combination

4.5.2 Quasi-permanent load combination

The stresses for the quasi-permanent load combination are presented in Tab. 4.6 and Tab. 4.7. Comments and explanations regarding the differences in the results are presented in the discussion chapter 4.5.3.

			At column	
		Hand calculations	ADAPT	FEM-Design
X-direction	Top fibre stresses	3,01 MPa	3,53 MPa	6,27 MPa
	Bottom fibre stresses	-6,55 MPa	-6,27 MPa	-9,45 MPa
Y-direction	Top fibre stresses	1,19 MPa	0,53 MPa	3,35 MPa
	Bottom fibre stresses	-3,57 MPa	-2,79 MPa	-5,71 MPa

Tab. 4.6 Stresses at column for quasi-permanent load combination

			At span	
		Hand calculations	ADAPT	FEM-Design
X-direction	Top fibre stresses	-5,12 MPa	-5,39 MPa	-5,02 MPa
	Bottom fibre stresses	1,58 MPa	2,97 MPa	1,97 MPa
Y-direction	Top fibre stresses	-1,82 MPa	-2,37 MPa	-2,26 MPa
	Bottom fibre stresses	-0,55 MPa	0,22 MPa	-0,15 MPa

Tab. 4.7 Stresses at span for quasi-permanent load combination

4.5.3 Discussion

The first obvious difference in the results are the large values FEM-Design has for the stresses at column. The reason for this is that hand calculations and ADAPT calculations are based on a full width strip, where the bending moments from dead and live loads are averaged over the cross section. The stresses calculated will then be the same throughout the whole width of the strip. Results from FEM-Design is based on average moments on a smaller design strip, and hence, the moments will have a larger value since the bending moments are larger closer to the columns. The different results are illustrated by Fig. 4.21. Further explanations on why it is sufficient to use the mean moments for designing is presented in chapter 2.3.6. Stresses at span from FEM-Design will correspond better since the bending moments used here will be approximate the same across the entire width.

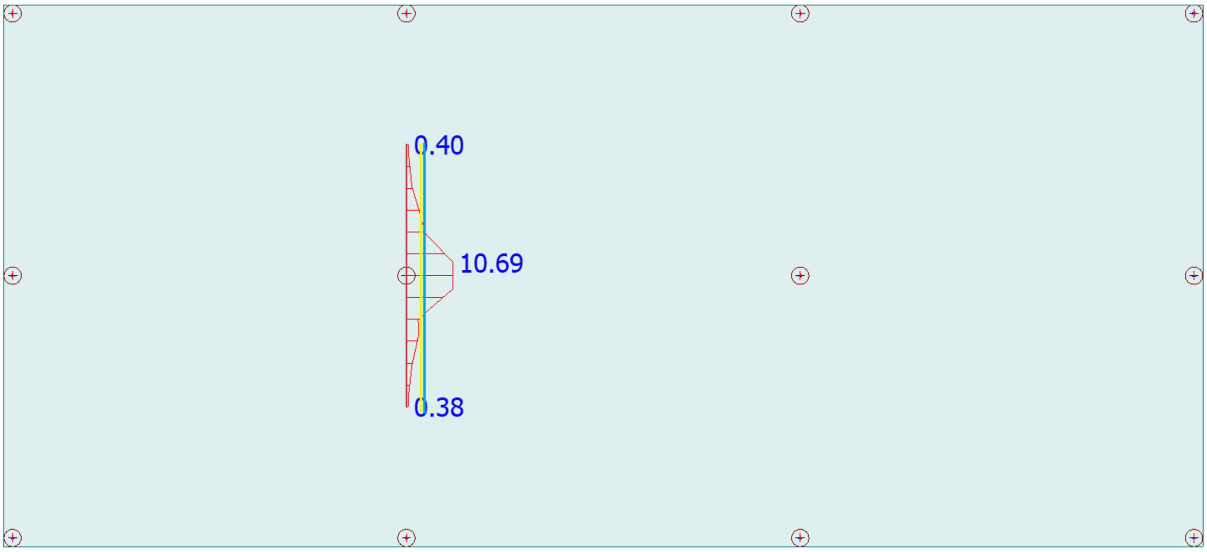


Fig. 4.21 Top fibre stresses at column in x-direction for quasi-permanent load combination - values and red lines represents FEM-Design results, yellow line represents hand calculations, and blue line represents ADAPT results

Another obvious source of error is that the initial load combination in ADAPT uses the same prestressing force as in the quasi-permanent load combination, i.e. the losses of the prestressing force is larger than in reality. This will hence give an average prestress in the structure that is less than real.

Results from hand calculations will differ from the other because of the total losses for the quasi-permanent load combination is according to the results in chapter 4.3. The losses for hand calculations are smaller than calculated in the programs, leading to a larger compression force from the tendons in hand calculations.

The calculations are based on gross cross sections, meaning that the area and moment of inertia is not transformed to account for the tendons and reinforcement. The centroidal axis is also assumed to be in the middle of the slab. These assumptions will cause minor errors to the results but will not be of significant size.

The bending moments and the stresses at columns in ADAPT and FEM-Design is taken from a design section right outside the column edge while the hand calculations are based on the maximum moments from simple beam theory, which is at the centre of the columns. Design sections at column edges will have more realistic bending moments.

In hand calculations the maximum bending moments in span and the maximum eccentricity of the tendons in span is assumed to be at the same place. This is not necessary true and will lead to small differences in the results. Hand calculations calculate the stresses at two places where the maximum values are expected. ADAPT calculates them for each design strip, i.e. 11 places for each span. FEM-Design has results for each node in the finite element model.

Many sources of error of the stress differences are presented. Taking everything into account, ADAPT is expected to give right values when using the full width approach. Obviously, the initial load combination will not be correct, as explained, and the long-term losses will not be correct if they are not determined and put in with the right values. FEM-Design is expected to give good results when no cracking of the concrete and redistribution of the bending moment is present. Due to the presented sources of error, the results cannot be directly compared, but the results are mostly in the same order of size and will hence validate the results.

4.6 Bending moment

The ultimate bending moments and capacities are calculated by hand and in ADAPT. FEM-Design has not been used in this check since the use of post-tensioning in the program is not sufficient for design purposes. The bending moments are checked at interior columns and in spans. Only the exterior span in x-direction are checked and compared. The live load is placed unfavourable for each case.

4.6.1 Ultimate bending moment

Hand calculations are presented in Appendix J. Bending moment envelopes from ADAPT is presented in Fig. 4.22 and Fig. 4.23. The ultimate bending moments at column and in span are presented in Tab. 4.8.

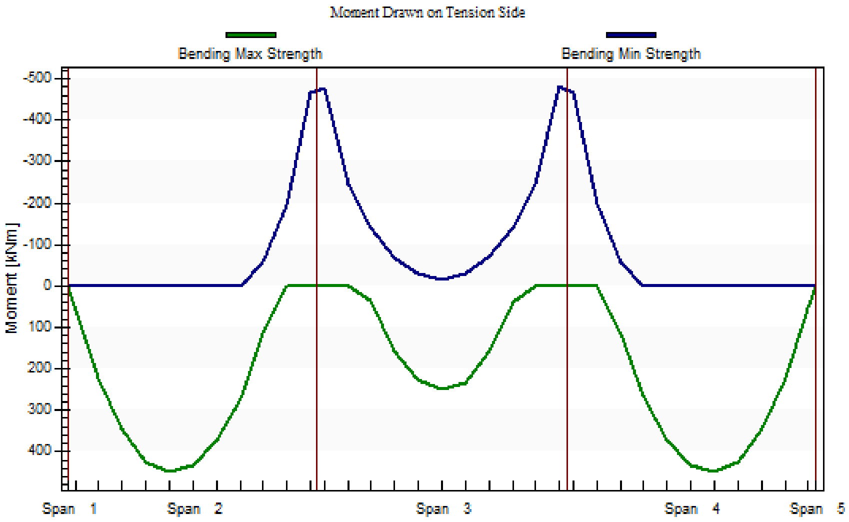


Fig. 4.22 Moment envelope in x-direction - ADAPT

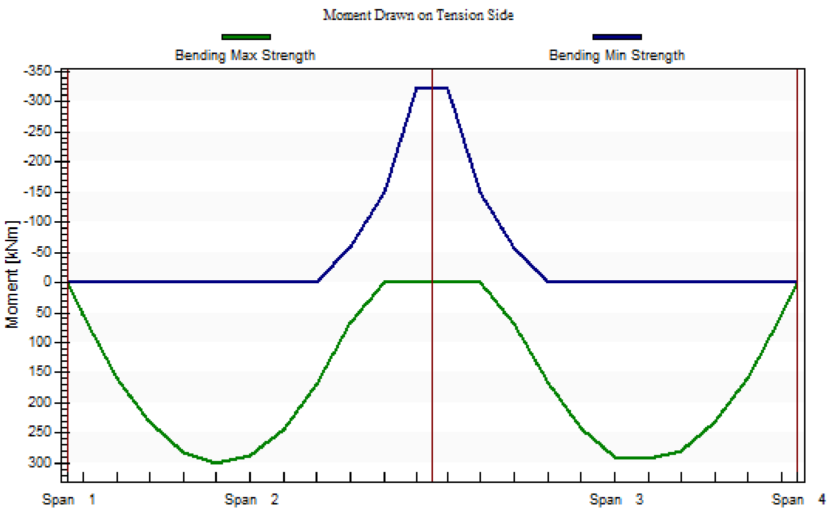


Fig. 4.23 Moment envelope in y-direction - ADAPT

		Hand calculations	ADAPT
X-direction	At column	-527,5 kNm	-481,0 kNm
	In spans	457,3 kNm	447,6 kNm
Y-direction	At column	-376,1 kNm	-323,4 kNm
	In spans	290,6 kNm	299,8 kNm

Tab. 4.8 Ultimate bending moments

The differences can be explained by two reasons. At columns, the hand calculation will have larger values since the bending moment is calculated at the centre of column, while ADAPT calculates it at the design section at the column edge. Also, the way ADAPT calculates the hyperstatic moment differs from the method used in hand calculations, which is described in chapter 2.3.7.1. ADAPT uses a direct method. In flat slabs, the indirect method used in hand calculations will not have correct results [16], and therefore, the results from ADAPT is expected to be correct. The hyperstatic moments from ADAPT is presented in Fig. 4.24 and Fig. 4.25. The maximum hyperstatic moment by the indirect method is 20kNm and 49kNm in respectively x- and y-direction.

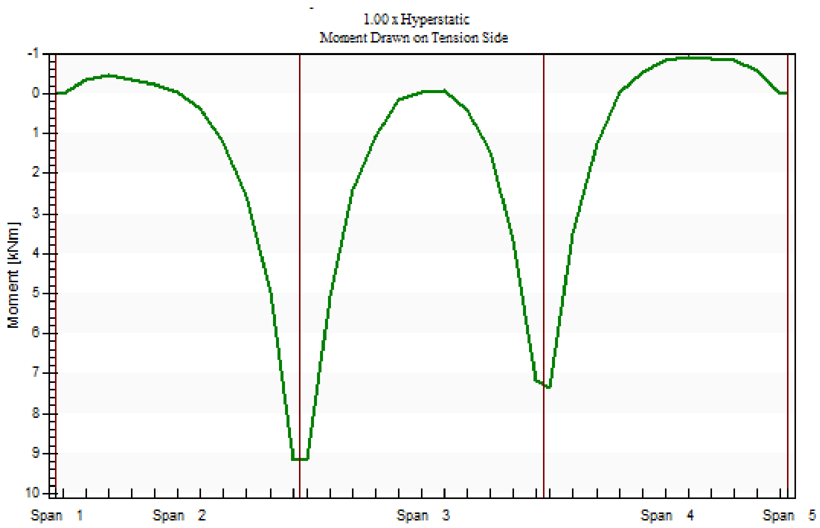


Fig. 4.24 Hyperstatic moment in x-direction - ADAPT

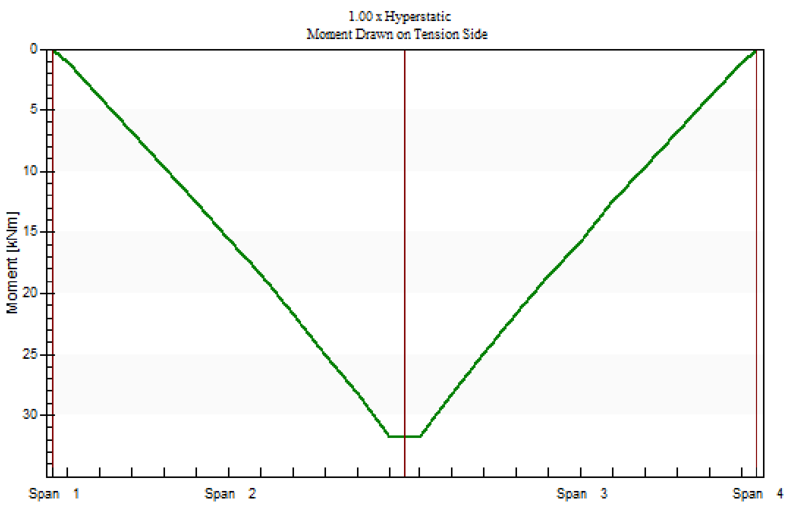


Fig. 4.25 Hyperstatic moment in y-direction - ADAPT

4.6.2 Ultimate bending moment capacity

Hand calculations are presented in Appendix J. The moment capacities and utilizations are compared in Tab. 4.9. Bending moments with capacity along the support line in ADAPT are presented in Fig. 4.26 and Fig. 4.27.

		Hand calculations	ADAPT
X-direction	At column	-383,2 kNm (138%)	-316,6 kNm (152%)
	In spans	337,9 kNm (135%)	312,3 kNm (143%)
Y-direction	At column	-472,2 kNm (80%)	-385,3 kNm (84%)
	In spans	483,4 kNm (60%)	392,4 kNm (76%)

Tab. 4.9 Bending moment capacities and utilizations

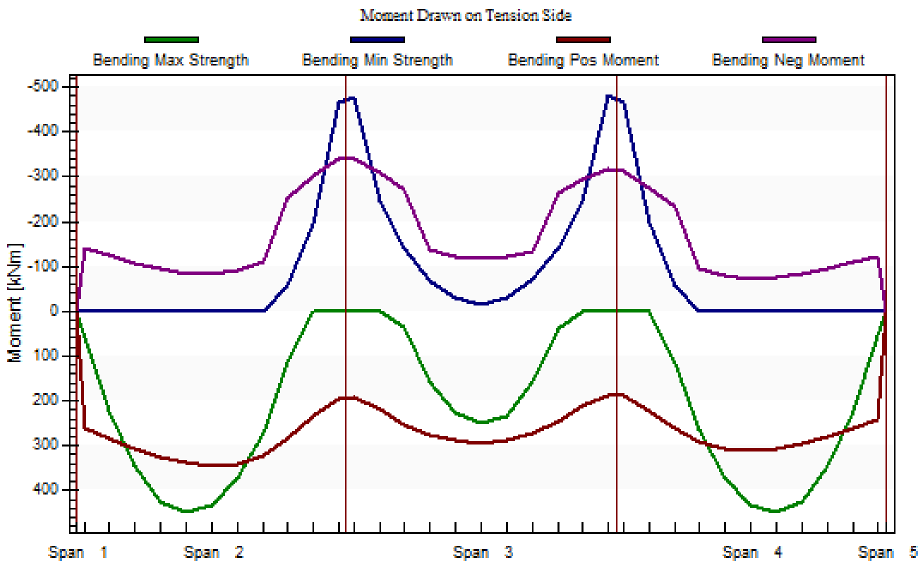


Fig. 4.26 Bending moments and capacity in x-direction – ADAPT

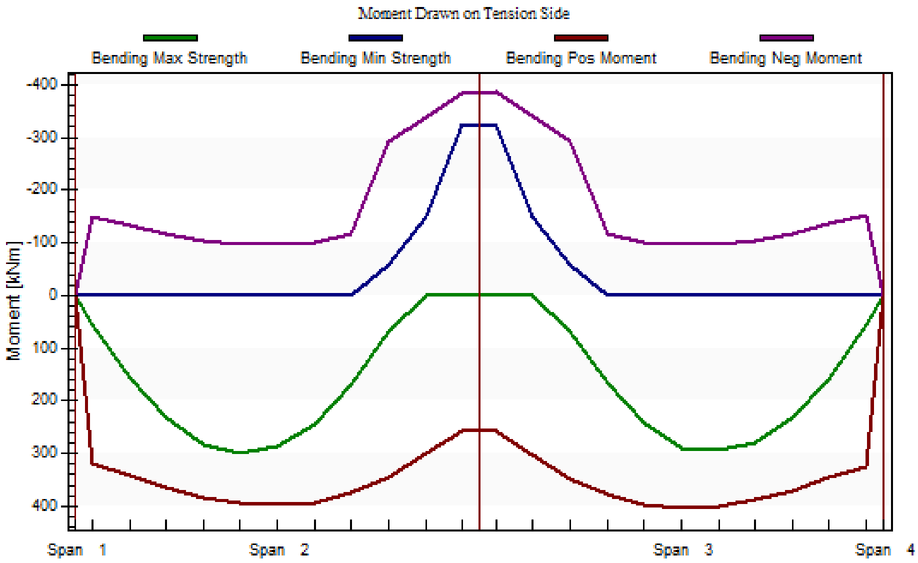


Fig. 4.27 Bending moments and capacity in y-direction - ADAPT

Differences in the results from hand calculations and ADAPT is explained by different prestressing force used. As presented previously, the losses used in hand calculations are smaller, and will hence lead to a larger contribution of the tendons on the capacity. Differences in the method of calculations may also be a source of error.

Extra reinforcement is needed in x-direction for the flat slab to be a sufficient design. ADAPT calculates this extra amount to be 23 ø10 in bottom in spans and 29 ø10 in top at column. This results in a utilization of 99% in both places. By comparison, the hand calculations with the same amount of extra reinforcement will result in a utilization of 128% at column and 106% in span. The big difference at column is due to the design bending moment in hand calculation being at centre of column, not at the edge. Other differences can be explained by the effective width of the section used in hand calculations being conservative.

4.7 Calculation of shear capacity

Shear calculations are done by hand. ADAPT can perform a punching shear check, but this is based on American code requirements, and the calculation method has not been investigated. For hand calculations, see Appendix K. The results are presented in Tab. 4.10 and Tab. 4.11.

	Inner column		Edge column		Corner column	
	At control perimeter	At column edge	At control perimeter	At column edge	At control perimeter	At column edge
v_{Ed} [MPa]	1,364	3,613	1,025	2,715	0,823	2,180
v_{Rd} [MPa]	0,828	2,894	0,731	2,483	0,731	2,483
Utilization	165%	125%	140%	109%	113%	88%

Tab. 4.10 Shear stresses and resistance with limitation

	Inner column	Edge column	Corner column
v_{Ed} [MPa]	3,613	2,715	2,180
v_{Rd} [MPa]	4,087	4,087	4,087
Utilization	88%	66%	53%

Tab. 4.11 Shear stresses and resistance at column edge without limitation

The conclusion of the results is that all columns requires shear reinforcement and the required shear reinforcement for inner and edge columns must be calculated without the concrete contribution. Only shear reinforcement on the inner columns has been calculated. The result is 16 stud rails with 5 studs each. For comparison, ADAPT´s result is 16 stud rails with 8 studs each. In the further part of this thesis shear stresses are only checked to be less than the maximum shear resistance. The amount of shear reinforcement will not be affected much by differences in the tendon layout and will hence not be a decisive part in the thesis. It should be noted that increasing the concrete strength could be sufficient due to the shear capacity for this flat slab design.

5 Tendon layout analysis

To analyse the influence the tendon layout has on the results of flat slabs, three slabs with different span lengths and parameters have been investigated with several tendon layouts.

5.1 Parameters

5.1.1 Flat slabs

The slabs have the same design as previously (3x2 spans with hinged circular columns), but other parameters have been used. They are presented in Tab. 5.1. Different concrete classes are used to get a sufficient shear strength. The design of the columns has not been checked.

	Span lengths [m]	6x6	9x6	11x6
	Slab thickness [mm]	180	220	270
	Column diameter [mm]	300	400	500
	f_{ck} [MPa]	35	45	45
	Creep coefficient	2,29	1,80	1,74
	Shrinkage coefficient [‰]	0,49	0,47	0,47
Minimum reinforcement	Bottom mesh	ø10 cc300	ø10 cc200	ø12 cc230
	Top, over columns, x-direction	8 ø16	12 ø16	14 ø16
	Top, over columns, y-direction	8 ø16	16 ø16	24 ø16

Tab. 5.1 Flat slab parameters

5.1.2 Prestressing

The tendon profiles are chosen to have maximum eccentricity at column and in spans. This results in clashing of the tendons. For the analysis this has been neglected but clashing of tendons are discussed further in chapter 5.2.5.

The amount of prestressing is chosen based on the procedure shown in Appendix D. In the analysis, ADAPT uses an effective prestressing force based on 20% losses, and FEM-Design uses prestressing forces based on estimated losses. This will cause some differences in the results. Since ADAPT uses the total losses also for the initial load combination, a factor of 1,1 is multiplied with the prestressing action. This will correspond to immediate losses of 12%. The initial prestressing force will hence not be real but accounted for to some extent. FEM-Design uses two different load cases for initial and quasi-permanent. Chosen prestressing is presented in Tab. 5.2.

		6x6	9x6	11x6
Maximum eccentricity	Top	23 mm	43 mm	68 mm
	Bottom	35 mm	55 mm	76 mm
Maximum drape (idealized profile)		47 mm	77 mm	110 mm
Number of tendons	X-direction	14	24	30
	Y-direction	22	34	46
Average compression in slab	X-direction	1,13 MPa	1,57 MPa	1,59 MPa
	Y-direction	1,19 MPa	1,01 MPa	0,91 MPa
Dead load balanced	X-direction	47%	47%	46%
	Y-direction	49%	68%	89%

Tab. 5.2 Prestressing parameters

5.1.3 Tendon layouts

Five different tendon layouts have been analysed in addition to a "layout" without any tendons. The different layouts are shown in chapter 5.1.3.1 to 5.1.3.6. Some of the lines in the following figures may consist of several tendons, i.e. banded tendons over columns is represented by one or two lines. It is not shown in the figures how many tendons each line represents, but the total number of tendons in each direction will be the same for all layouts. The presented flat slabs have span lengths of 11m and 6m. The layouts will be similar for the flat slabs with other span lengths, but with different number of tendons.

5.1.3.1 Tendon layout A

Banded in direction with longest span and distributed in the other direction.

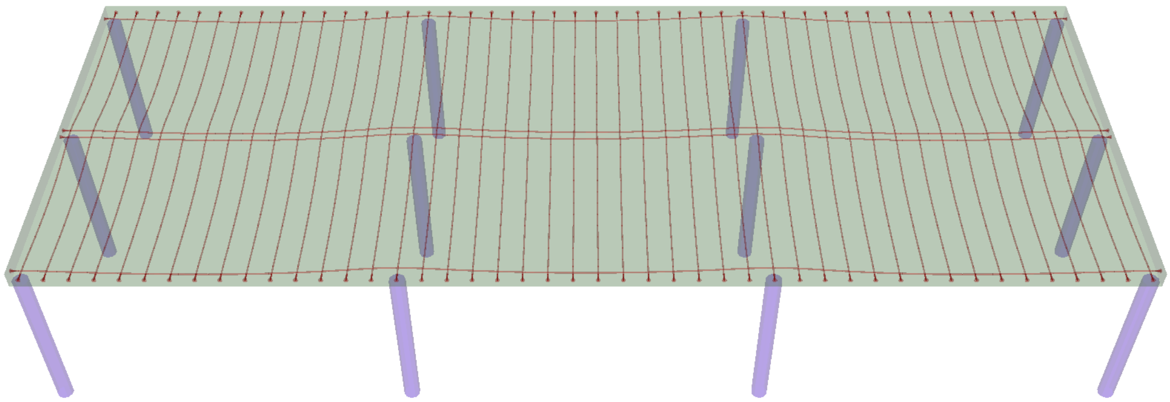


Fig. 5.1 Tendon layout A

5.1.3.2 Tendon layout B

Banded in both directions.

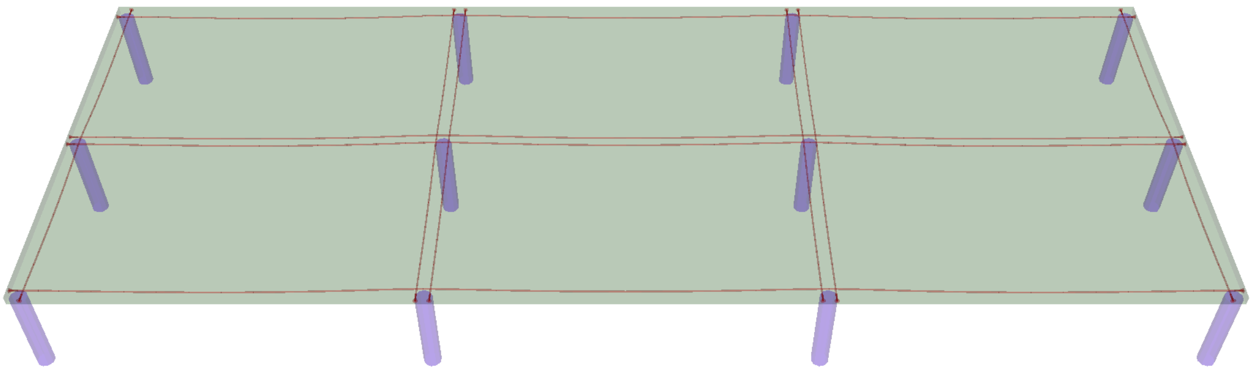


Fig. 5.2 Tendon layout B

5.1.3.3 Tendon layout C

Banded in the direction with shortest span and distributed in the other.

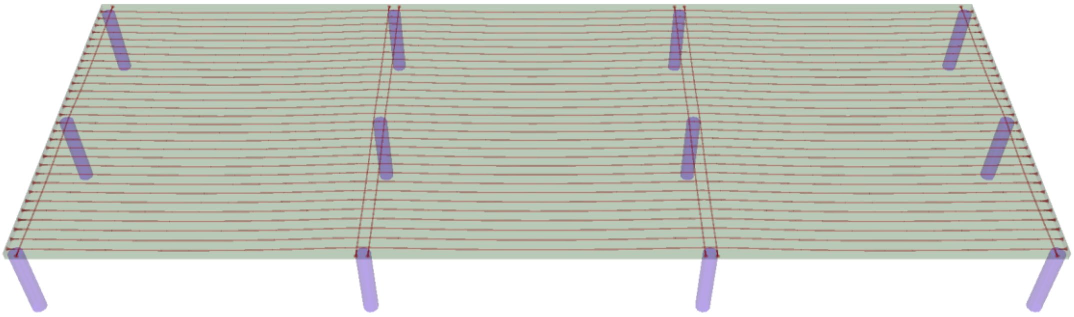


Fig. 5.3 Tendon layout C

5.1.3.4 Tendon layout D

About 50% of tendons are banded and 50% are distributed in direction with longest span. Banded in the other direction.

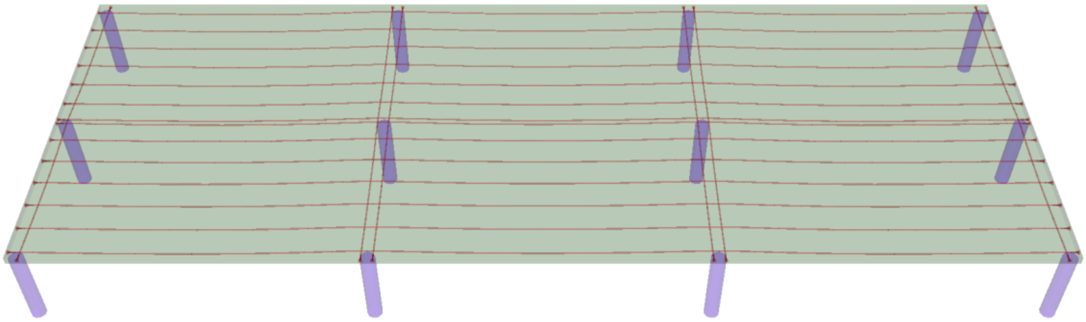


Fig. 5.4 Tendon layout D

5.1.3.5 Tendon layout E

About 50% banded and 50% distributed in both directions.

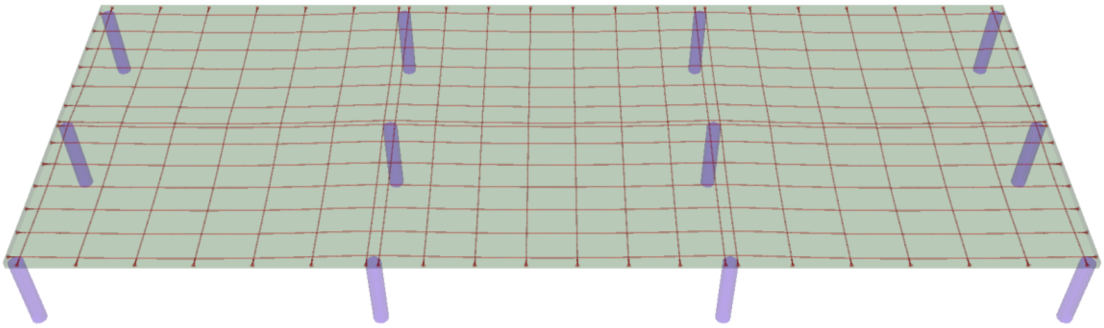


Fig. 5.5 Tendon layout E

5.1.3.6 Tendon layout F

No tendons/prestressing. Is named “tendon layout F” but contains no tendons.

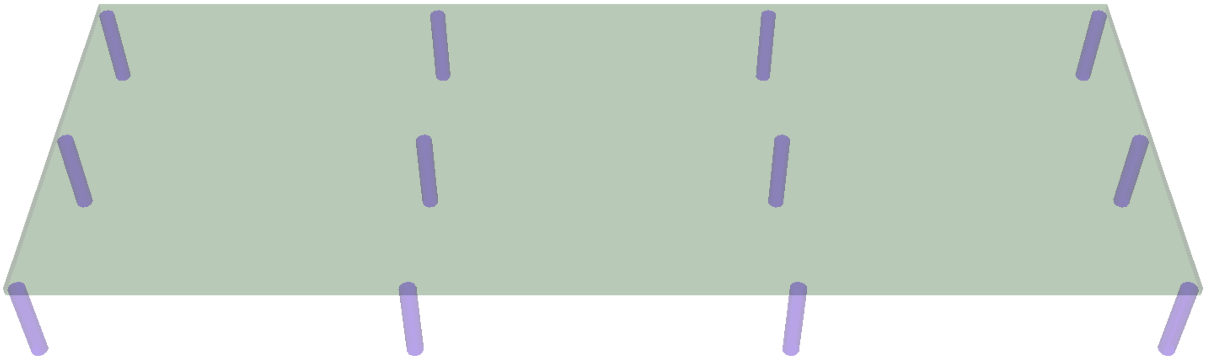


Fig. 5.6 Tendon layout F

5.2 Results & discussion

5.2.1 Deflections at SLS

The maximum deflections for the flat slabs are presented in Tab. 5.3.

		Initial		Long-term	
		ADAPT	Fem-Design	ADAPT	Fem-Design
6X6	A	-2,0	-2,1	-9,0	-12,3
	B	-1,9	-1,9	-8,8	-12,0
	C	-2,0	-2,1	-9,1	-12,4
	D	-2,0	-2,0	-8,9	-12,3
	E	-2,0	-2,1	-9,0	-12,4
	F	-4,0	-4,5	-14,4	-19,4
9X6	A	-4,0	-4,3	-17,6	-19,4
	B	-3,5	-3,6	-16,4	-17,8
	C	-3,8	-3,7	-16,9	-17,9
	D	-3,6	-3,6	-16,6	-17,7
	E	-3,8	-3,9	-17,0	-18,2
	F	-8,5	-9,1	-30,1	-31,1
11X6	A	-5,7	-6,0	-23,6	-20,3
	B	-5,1	-5,0	-22,0	-18,1
	C	-5,7	-5,6	-23,7	-18,8
	D	-5,2	-5,1	-22,5	-18,0
	E	-5,5	-5,5	-23,2	-19,0
	F	-11,7	-12,3	-40,1	-35,1

Tab. 5.3 Tendon layout analysis – Deflections [in mm]

Results from ADAPT and FEM-Design will differ because of some differences in the prestressing force used and the way creep and shrinkage are accounted for in the two programs for the long-term deflection.

Generally, the results show that compared to layout F without tendons, the differences between layout A – E are not huge. Deflections in layout F are more than twice the deflection with prestressing actions in the initial load combination, and for the long-term combination the effect is also major.

The results also show that the tendon layouts with the least number of distributed tendons (layout B and D) has the smallest deflections. For an idealized tendon profile, one would expect the opposite, that the layouts with more distributed tendons would better counteract the dead load as a more uniform upward load. The case is that realistic tendon profiles will result in downward equivalent forces in some areas. The equivalent loads from the tendon profile in x-direction for the 11x6 slab is presented in Fig. 5.7. When a tendon is concentrated, these downward forces will be at the top of the columns, and not lead to any deflections. When a tendon is distributed, the downward force will be in spans, and hence increase the downward load in this area, resulting in increased deflections.

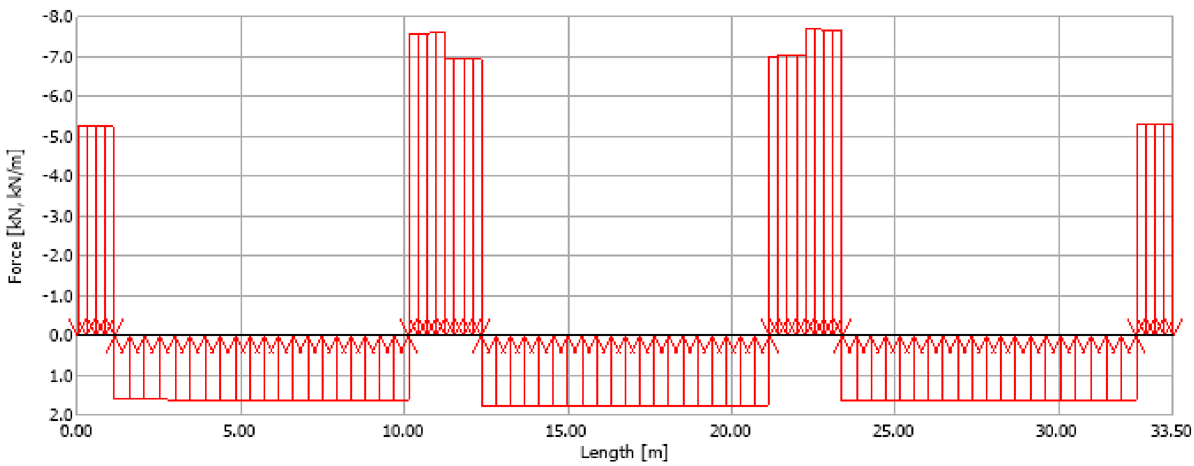


Fig. 5.7 Equivalent loads for tendon profile in x-direction for 11x6 slab

5.2.2 Stresses at SLS

The results are taken at the control points shown in Fig. 5.8. The load combination used for this analysis is the quasi-permanent combination. The results are presented in Tab. 5.4. The results have been presented with one decimal to easier detect differences. For results with two decimals, see Appendix L.

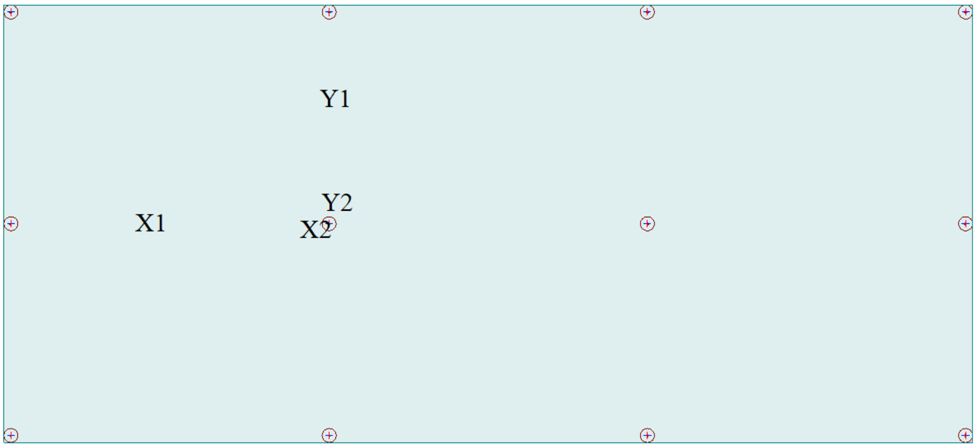


Fig. 5.8 Control points

		ADAPT				Fem-Design			
		X1 (span)		X2 (column)		X1 (span)		X2 (column)	
		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
6X6	A	-3,0	0,5	0,9	-3,2	-3,6	0,3	6,7	-9,1
	B	-3,1	0,3	1,0	-3,1	-3,2	-0,4	4,7	-7,1
	C	-3,1	0,5	1,2	-3,2	-3,4	0,9	6,5	-8,7
	D	-3,1	0,5	1,1	-3,2	-3,2	0,4	5,8	-8,1
	E	-3,0	0,6	1,1	-3,2	-3,4	0,8	6,6	-9,0
	F	-	-	-	-	-3,6	3,6	11,6	-11,6
9X6	A	-4,5	1,5	2,0	-5,1	-5,0	1,6	8,5	-11,7
	B	-4,8	1,1	2,2	-4,8	-4,9	0,7	5,5	-8,3
	C	-5,0	1,0	2,2	-4,8	-5,0	1,0	6,6	-9,6
	D	-4,9	1,1	2,1	-4,8	-4,9	0,7	5,8	-8,8
	E	-4,7	1,3	2,1	-4,9	-4,9	1,1	6,9	-9,9
	F	-	-	-	-	-5,5	5,5	14,6	-14,6
11X6	A	-5,1	1,9	2,4	-5,6	-4,6	1,3	6,3	-9,5
	B	-5,4	1,4	2,8	-5,3	-4,6	0,4	2,8	-5,5
	C	-5,4	1,4	2,9	-5,4	-4,8	0,4	3,8	-6,6
	D	-5,4	1,5	2,8	-5,3	-4,6	0,4	3,2	-5,9
	E	-5,2	1,6	2,7	-5,5	-4,6	0,7	4,6	-7,6
	F	-	-	-	-	-5,5	5,5	12,6	-12,6

Tab. 5.4 Tendon layout analysis – Stresses in X-direction [in MPa] (tension is positive)

		ADAPT				Fem-Design			
		Y1 (span)		Y2 (column)		Y1 (span)		Y2 (column)	
		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
6X6	A	-2,8	0,3	1,3	-3,6	-2,8	0,3	6,6	-9,0
	B	-2,8	0,1	1,0	-3,4	-2,8	-0,7	4,8	-7,4
	C	-2,8	0,2	0,9	-3,4	-3,2	-0,3	6,8	-9,5
	D	-2,8	0,2	1,0	-3,4	-3,2	-0,3	5,9	-8,6
	E	-2,8	0,3	1,1	-3,5	-3,2	0,2	6,7	-9,3
	F	-	-	-	-	-3,1	3,1	12,0	-12,0
9X6	A	-2,0	-0,1	0,2	-2,3	-2,3	0,3	7,1	-9,3
	B	-2,0	-0,2	0,1	-2,2	-2,1	-2,0	3,6	-6,4
	C	-2,0	-0,1	0,2	-2,2	-2,4	-1,2	5,8	-8,5
	D	-2,0	-0,2	0,1	-2,2	-2,4	-1,7	4,4	-7,2
	E	-2,0	-0,2	0,1	-2,2	-2,5	-1,0	5,6	-8,2
	F	-	-	-	-	-3,2	3,2	13,0	-13,0
11X6	A	-1,6	-0,2	-0,1	-1,7	-1,5	-0,5	4,5	-6,4
	B	-1,6	-0,4	-0,2	-1,6	-1,3	-3,0	0,0	-2,9
	C	-1,6	-0,3	-0,2	-1,6	-2,0	0,2	2,1	-4,9
	D	-1,6	-0,4	-0,2	-1,6	-1,6	-2,7	0,8	-3,7
	E	-1,6	-0,3	-0,2	-1,7	-1,6	-1,6	2,7	-5,1
	F	-	-	-	-	-2,3	2,3	10,2	-10,2

Tab. 5.5 Tendon layout analysis – Stresses in Y-direction [in MPa] (tension is positive)

In ADAPT, there are small differences in the results between the tendon layouts. This is because it uses average values across the design strips. Using the full width approach, the design stresses will have small variations. For a better comparison of the stress contribution the tendon layout has, the results from FEM-Design have been looked closer into.

As opposite to the stress results in chapter 4.5, the results have not been averaged here. Results in FEM-Design is hence the maximum values which in ADAPT have been averaged. The results are hence not comparable with each other.

From the results one can see that the biggest differences are in the stresses at column. It is in this area the largest stresses are, and compared with layout F, this is where the impact of the prestressing is largest. Results show that the tensile stresses in top fibre at column will be smallest when using banded tendons. This implies that tendon layout B has the best effect on stresses. To show this graphically, results for top fibre stresses in x-direction is presented in Fig. 5.10 - Fig. 5.14 for the different layouts with only the prestressing actions applied. Fig. 5.9 shows the top fibre stress with only the dead load and permanent part of the live load included.

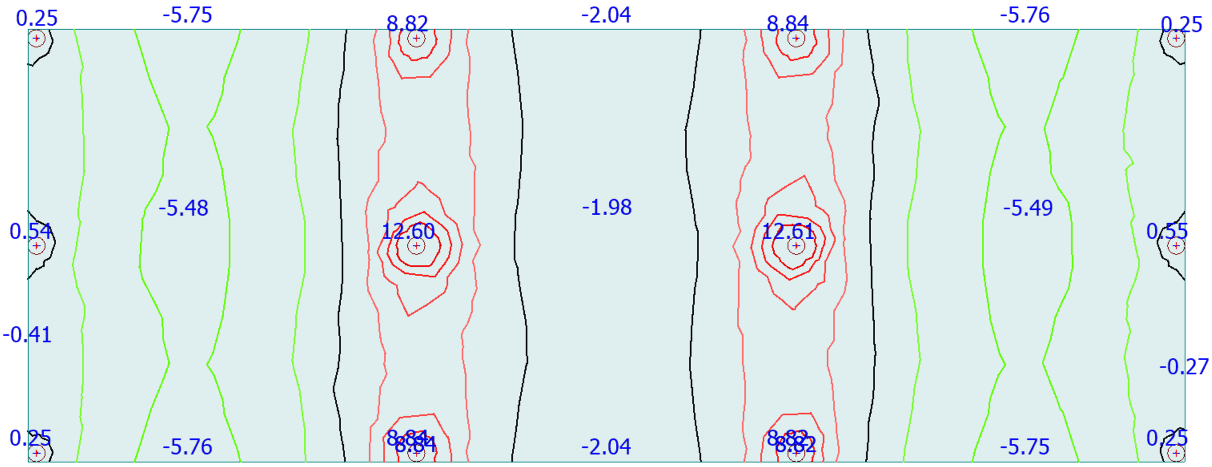


Fig. 5.9 Stresses in top fibre in x-direction due to quasi-permanent load combination with prestressing action excluded [MPa]

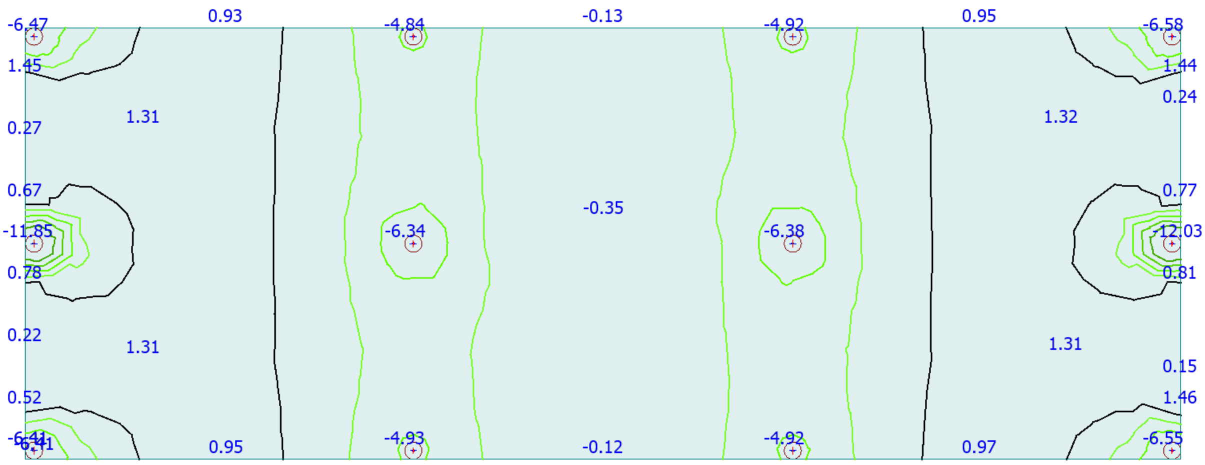


Fig. 5.10 Stresses in top fibre x-direction due to prestressing actions – Tendon layout A [MPa]

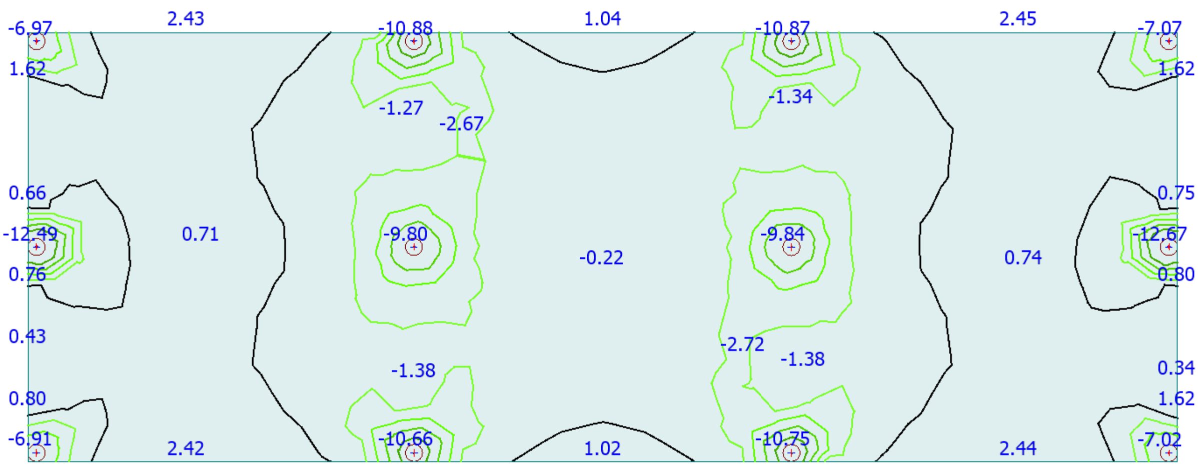


Fig. 5.11 Stresses in top fibre x-direction due to prestressing actions – Tendon layout B [MPa]

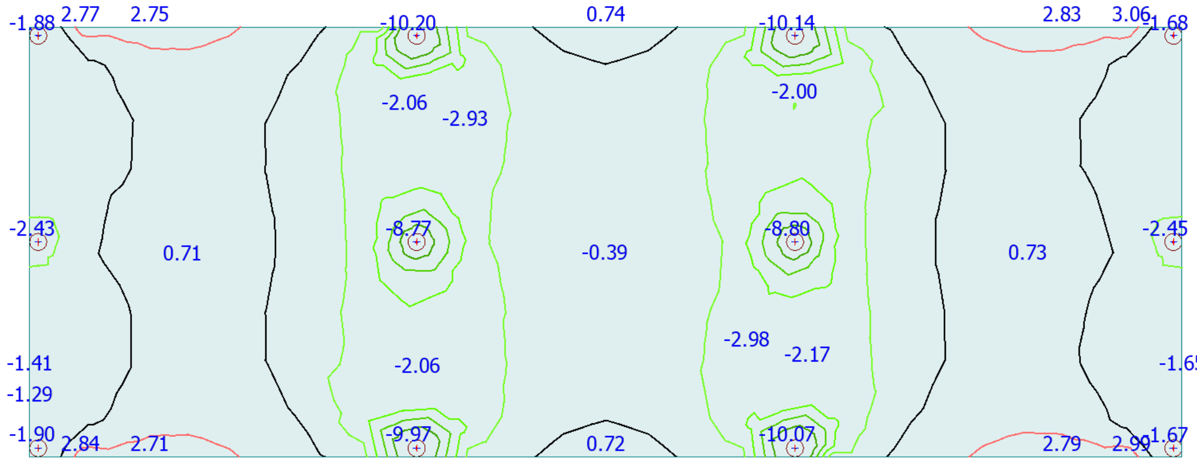


Fig. 5.12 Stresses in top fibre x-direction due to prestressing actions – Tendon layout C [MPa]

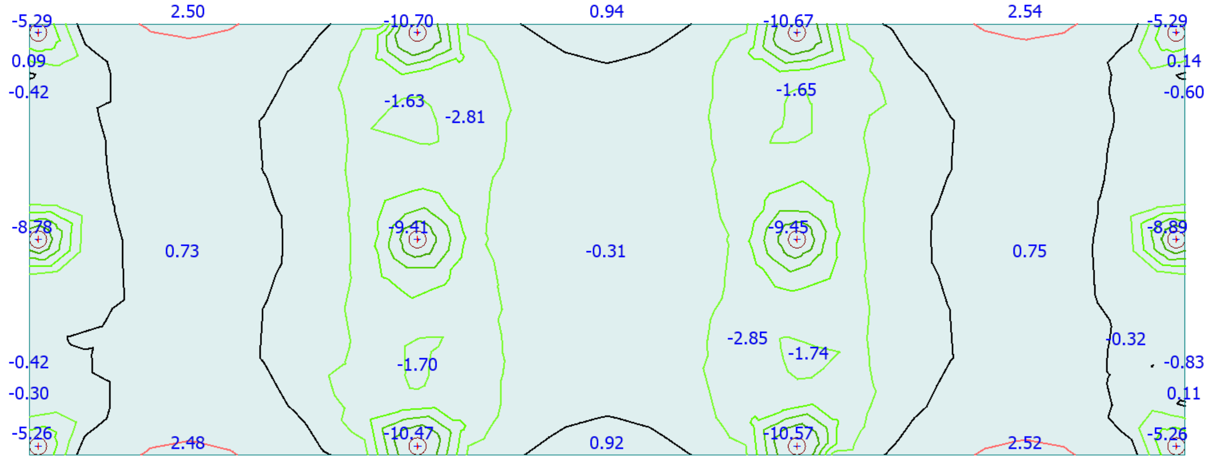


Fig. 5.13 Stresses in top fibre x-direction due to prestressing actions – Tendon layout D [MPa]

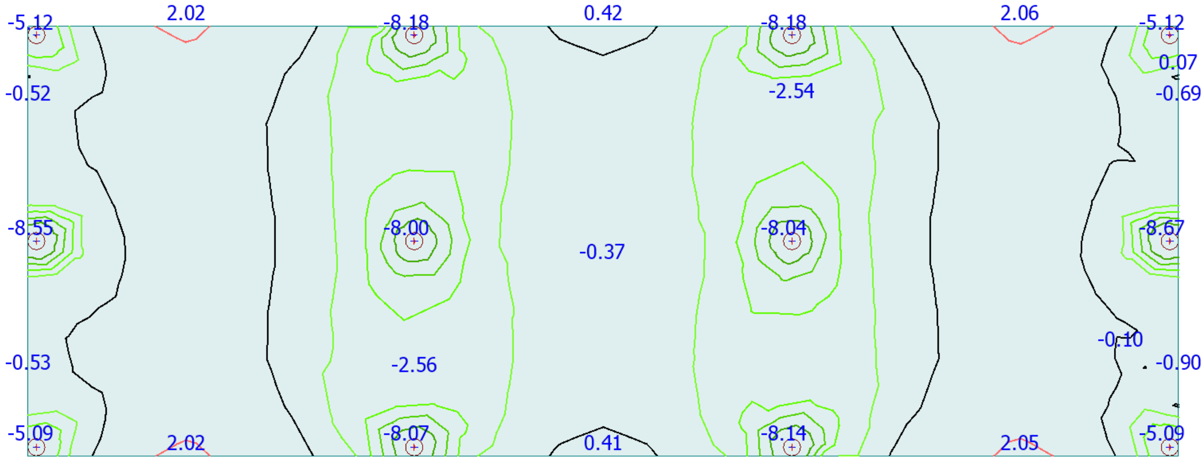


Fig. 5.14 Stresses in top fibre x-direction due to prestressing actions – Tendon layout E [MPa]

5.2.3 Bending moments at ULS

Since ADAPT is based on full width design sections, there are small differences in the bending moment capacities for the different tendon layouts. Too better see which layouts that has the best placing due to the bending moments in the slab, hand calculations due to a column strip / middle strip approach is done for the 9x6 slab. The calculations are shown in Appendix M. The design bending moments are distributed between the column and middle strip. Negative moments are distributed 70/30% and positive moments are distributed 60/40% which is in accordance with Tab. 2.3. Utilization results are presented in Tab. 5.6.

	X-direction				Y-direction			
Tendon layout	Column strip		Middle strip		Column strip		Middle strip	
	At column	In spans	At column	In spans	At column	In spans	At column	In spans
A	85%	70%	268%	200%	122%	87%	26%	32%
B	85%	70%	268%	200%	57%	47%	130%	64%
C	134%	108%	67%	73%	57%	47%	130%	64%
D	113%	91%	91%	91%	57%	47%	130%	64%
E	113%	91%	91%	91%	79%	60%	51%	41%
F	316%	300%	268%	200%	241%	192%	130%	64%

Tab. 5.6 Bending moment utilizations for a column strip/middle strip approach

As expected, concentrated tendons will lead to good capacities in column strips and low in middle strips. The best results are where tendons are both concentrated and placed in spans (Layout E and x-direction for layout D).

5.2.4 Shear at ULS

There will be no large differences between the tendon layouts due to shear capacity for interior columns. The total prestressing is the same, and hence the increase in shear strength due to prestressing will also be the same. For columns close to the edge where the compression stresses from the concentrated anchorages has not yet been distributed uniformly to the slab, there will be an increase in the punching shear capacity.

The shear capacity can be increased in a great extent if the tendons used are bonded instead of unbonded. Concentrating the tendons over columns would then be the most sufficient to increase the capacity. This has not been investigated further in this thesis.

5.2.5 Clashing of tendons

In the analysis the issue of intersecting tendons in opposite directions has not been accounted for when choosing the tendon profiles. ADAPT has a function that detects clashing of tendons. The results for tendon layout A – E for the 11x6 slab is presented in Fig. 5.15 - Fig. 5.19. Places where tendons are intersecting each other is represented with a small pink cross.

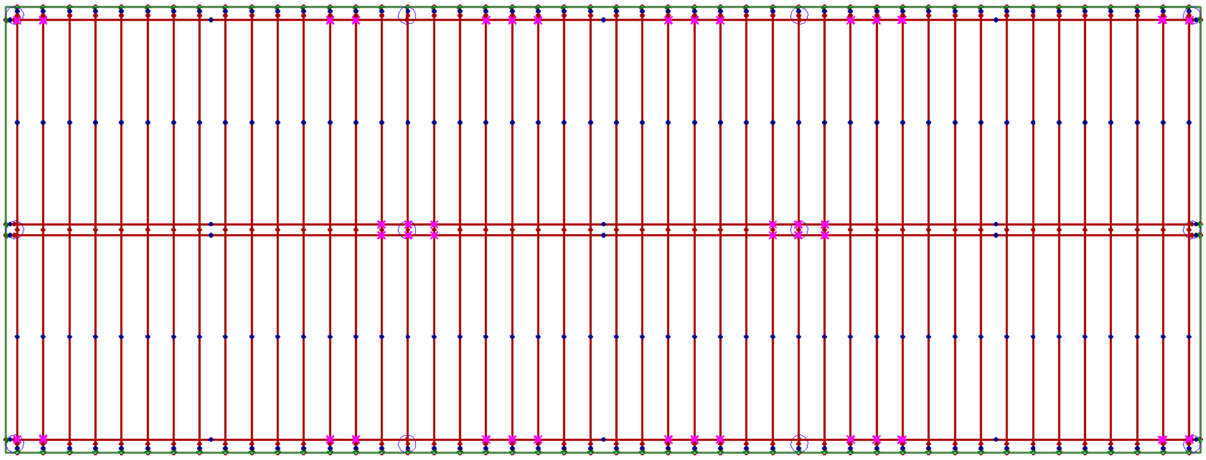


Fig. 5.15 Clashing of tendons – Tendon layout A

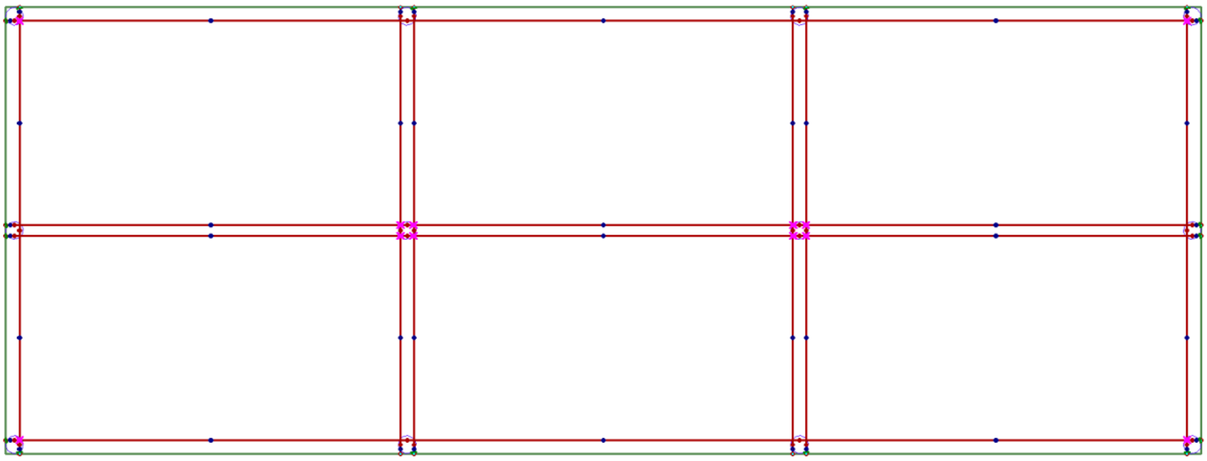


Fig. 5.16 Clashing of tendons – Tendon layout B

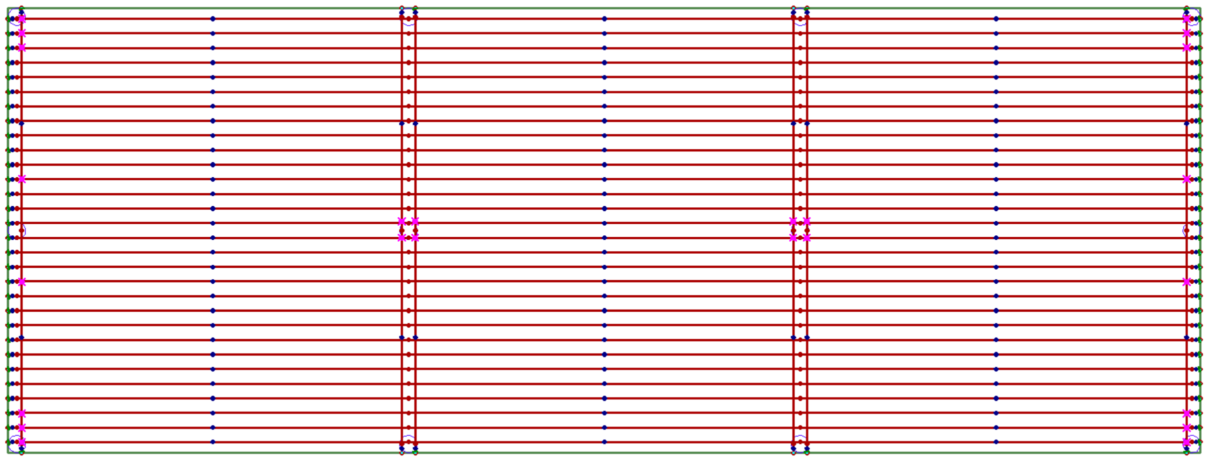


Fig. 5.17 Clashing of tendons – Tendon layout C

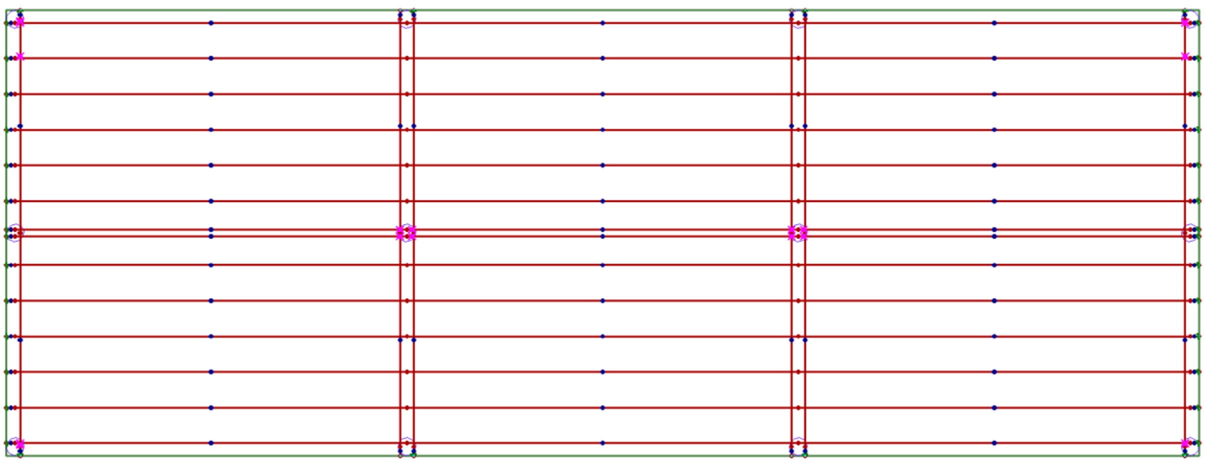


Fig. 5.18 Clashing of tendons – Tendon layout D

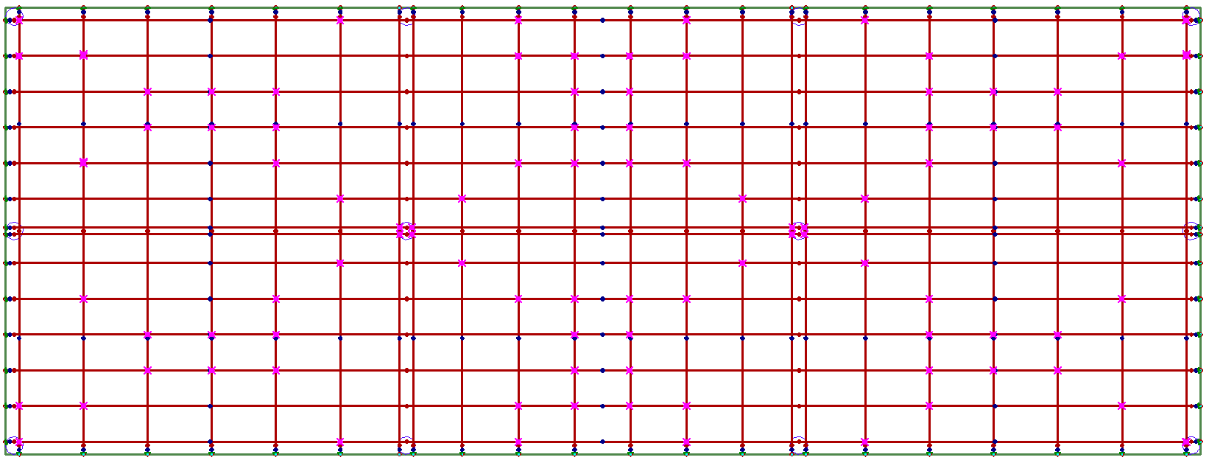


Fig. 5.19 Clashing of tendons – Tendon layout E

Tendon layout E has many intersecting tendons in spans, and it will cause weaving of tendons which will be expensive due to the extra amount of time it will take to change tendon profiles individually. The other layouts intersect at column and at edges. At column the issue can easily be solved by adjusting the tendon profile in one of the directions. For layout B, the tendons intersect in the corners. This can also easily be adjusted. For layout A, C and D, adjusting some of the tendon profiles individually may be necessary at the edges. Since banded tendons will be placed close to each other, it is expected that layout B will be the most economic layout due to placement costs.

6 Conclusion

Tendon layout E is a sufficient layout due to the tendons being placed according to the bending moments in the slab. Because of tendons in spans in both directions, a great extent of weaving is necessary for such a design. This would increase the time of the construction process, and hence it would normally not be economical. The results in terms of deflection and stresses are not the best either.

The most used layout today is concentrated tendons in one direction and distributed tendons in the other. Tendon layout A and C is such slabs, where A has distributed tendons in the short span direction and C in the long span direction. The results in terms of deflections, stresses and bending moments are better for layout C, which indicates that when designing a flat slab with unequal span lengths, the concentrated tendons should be in the shortest span direction (tendon layout C).

Layout D is a continuation of layout C, where some of the distributed tendons from C are concentrated over supports. This layout would distribute the tendons better in terms of the bending moments, and it will also give lower stresses and some reduction in deflections.

Tendon layout B has the best results in terms of stresses and deflections. Many tendons are banded, and the construction time would hence decrease compared to the other layouts. When looking at middle strips between columns, the bending moment capacity is low. In flat slabs with distributed tendons, these tendons will transfer the loads to the concentrated tendons which will transfer them to supports. Layout B has no distributed tendons and would hence require extra reinforcement in spans to be a sufficient design.

Reference list

[1] KB Spennteknikk AS, *BBR VT CONA Single spenntausystem*, 2011. Available: http://www.spennteknikk.no/brosjyrer/BBR-VT-CONA-Single-spenntausystem-24022011.pdf.

[2] T. Hagberg, *Publikasjon nr. 33 Flatdekker: Beregning og konstruktiv utforming*. Oslo: Norsk Betongforening, 2004.

[3] S. I. Sørensen, *Betongkonstruksjoner : beregning og dimensjonering etter Eurocode 2*, 2 ed. Trondheim: Fagbokforlaget, 2013.

[4] P. Bhatt, *Prestressed concrete design to Eurocodes*. Routledge, 2011.

[5] CCL, *Post-tensioned slabs*, 2017. Available: https://www.cclint.com/uploads/PDFs/Post-tensioned-Slabs.pdf.

[6] R. I. Gilbert, N. C. Mickleborough, and G. Ranzi, *Design of prestressed concrete to Eurocode 2*, 2 ed. CRC Press, 2017.

[7] Post-tensioning Institute, *PT Basics*. Available: http://www.post-tensioning.org/page/pt-basics. [Accessed: 31.01.2018].

[8] F. A. Zahn and H. R. Ganz, "Post-tensioned in buildings," VSL, Zurich, VSL report series 4.1, 1992, Available: https://www.vsl.net/sites/default/files/vsl/datasheet/PT_Buildings.pdf.

[9] B. O. Aalami and J. D. Jurgens, "Guidelines for the Design of Post-Tensioned Floors," 2003.

[10] *Building Code Requirements for Strutural Concrete (ACI 318-02) and Commentary (ACI 318R-02)*, ACI 318-02 and ACI 318R-02, 2002.

[11] *Eurokode 2: Prosjektering av betongkonstruksjoner - Del 1-1: Allmenne regler og regler for bygninger*, NS-EN 1992-1-1:2004+NA:2008, 2008.

[12] D. B. O. Aalami, "Prestressing Losses and Elongation Calculations," *Technical Note*, no. T9-04, 2004.

[13] *Eurokode: Grunnlag for prosjektering av konstruksjoner*, NS-EN 1990:2002+A1:2005+NA:2016, 2016.

[14] The Concrete Society, "Post-tensioned concrete floors Design Handbook," Technichal Report No. 43, 2005.

[15] H. Sælen, "Konsekvenser av irregulær ytre geometri for bæresystemets klimagassregnskap på Gullhaug Torg," Master thesis, Department of Structural Engineering, Norwegian University of Science and Technology, Trondheim, 2016.

[16] B. O. Aalami, "Hyperstatic (Secondary) Actions In Prestressing and Their Computation," 2010.

[17] StruSoft, *FEM-Design*. Available: https://strusoft.com/products/fem-design. [Accessed: 12.06.2018].

[18] ADAPT, *Integrated Reinforced Post-Tensioned Concrete Building Design Software*. Available: http://www.adaptsoft.com/software.php. [Accessed: 12.06.2018].

[19] B. O. Aalami, "Structural Modeling of Posttensioned Members," 2000.

[20] ADAPT Structural Concrete Software System, *ADAPT-FLOOR PRO USER MANUAL*, 2017. Available: http://www.adaptsoft.com/manuals/ADAPT-Builder_2017_User_Manual.pdf.

List of appendices

Appendix A	Cover
Appendix B	Creep and shrinkage
Appendix C	Minimum reinforcement
Appendix D	Load balancing
Appendix E	Modelling progress in FEM-Design 17
Appendix F	Modelling progress in ADAPT-Floor Pro
Appendix G	Losses of prestress
Appendix H	Angular displacement for friction loss calculations
Appendix I	Stress calculations
Appendix J	Bending moment calculations
Appendix K	Shear calculations
Appendix L	Stresses in tendon layout analysis with two decimals
Appendix M	Bending moment capacities due to a column strip/middle strip approach

Appendix A - Cover

The flat slab is for an office, indoor with low air humidity, and 50 year:

(EC2-1-1: Tab.4.1) Exposure class: XC1

Cover to steel reinforcement:

(EC2-1-1: Tab NA.4.2) $c_{min.b} := 10mm$ (reinforcement ø10)

(EC2-1-1: Tab. NA.4.5N) $c_{min.dur} := 15mm$

(EC2-1-1: NA.4.4.1.2(6)) $\Delta c_{dur.\gamma} := 0mm$

(EC2-1-1: NA.4.4.1.2(7)) $\Delta c_{dur.st} := 0mm$

(EC2-1-1: NA.4.4.1.2(8)) $\Delta c_{dur.add} := 0mm$

(EC2-1-1: NA.4.4.1.3(1)P) $\Delta c_{dev} := 10mm$

(EC2-1-1: 4.4.1.2(2)P)

$$c_{min} := \max\left(c_{min.b}, c_{min.dur} + \Delta c_{dur.\gamma} - \Delta c_{dur.st} - \Delta c_{dur.add}, 10mm\right) = 15 \cdot mm$$

(EC2-1-1: 4.4.1.1(2)P) $c_{nom.s} := c_{min} + \Delta c_{dev} = 25 \cdot mm$

Cover to tendon:

(EC2-1-1: Tab NA.4.2) $c_{min.b} := 1.5 \cdot 20mm$ (tendon tube ø20)

(EC2-1-1: Tab. NA.4.5N) $c_{min.dur} := 25mm$

(EC2-1-1: NA.4.4.1.2(6)) $\Delta c_{dur.\gamma} := 0mm$

(EC2-1-1: NA.4.4.1.2(7)) $\Delta c_{dur.st} := 0mm$

(EC2-1-1: NA.4.4.1.2(8)) $\Delta c_{dur.add} := 0mm$

(EC2-1-1: NA.4.4.1.3(1)P) $\Delta c_{dev} := 10mm$

(EC2-1-1: 4.4.1.2(2)P)

$$c_{min} := \max\left(c_{min.b}, c_{min.dur} + \Delta c_{dur.\gamma} - \Delta c_{dur.st} - \Delta c_{dur.add}, 10mm\right) = 30 \cdot mm$$

(EC2-1-1: 4.4.1.1(2)P) $c_{nom.p} := c_{min} + \Delta c_{dev} = 40 \cdot mm$

Appendix B - Creep and shrinkage

ref NS-EN 1992-1-1, clause 3.1.4 and annex B
(calculations are made nondimensional, input is in newton (N) og millimeter (mm))

Concrete: B35 $f_{ck} := 35$ $f_{cm} := f_{ck} + 8 = 43$

Realtive humidity (%): $RH := 40$ (Assumed 40% for indoor construction)

Creep

Width of slab section: $b := 1000$

Slab thickness: $h := 200$

Area exposed to air: $u := 2(b) = 2000$

Area of the cross section: $A_c := h \cdot b = 200000$

Effective thickness of cross section: $h_0 := \dfrac{2 \cdot A_c}{u} = 200$

Age of concrete (70 years): $t := 25550$

Age of concrete when loading: $t_0 := 28$

$$\beta_{fcm} := \frac{16.8}{\sqrt{f_{cm}}} = 2.562$$

$$\beta_{t0} := \frac{1}{0.1 + t_0^{\,0.2}} = 0.488$$

$$\alpha_1 := \left(\frac{35}{f_{cm}}\right)^{0.7} = 0.866 \qquad \alpha_2 := \left(\frac{35}{f_{cm}}\right)^{0.2} = 0.96 \qquad \alpha_3 := \left(\frac{35}{f_{cm}}\right)^{0.5} = 0.902$$

$$\beta_H := \min\left[1.5 \cdot \left[1 + (0.012 \cdot RH)^{18}\right] \cdot h_0 + 250, 1500\right] = 550.001$$

$$\beta_{c.t.t0} := \left(\frac{t - t_0}{\beta_H + t - t_0}\right)^{0.3} = 0.994$$

$$\phi_{RH} := \left[1 + \left(\frac{1 - \frac{RH}{100}}{0.1\cdot\sqrt[3]{h_0}}\right)\cdot\alpha_1\right]\cdot\alpha_2 = 1.812$$

Ntional creep coefficient: $\phi_0 := \phi_{RH}\cdot\beta_{fcm}\cdot\beta_{t0} = 2.268$

Creep coefficient: $\phi_{t.t0} := \phi_0\cdot\beta_{c.t.t0} = 2.253$

Shrinkage

Cementclass: N

$f_{cmo} := 10$

$RH_0 := 100$

$$\beta_{RH} := 1.55\cdot\left[1 - \left(\frac{RH}{RH_0}\right)^3\right] = 1.451$$

$\alpha_{ds1} := 4$

$\alpha_{ds2} := 0.12$

$$\varepsilon_{cd.0} := 0.85\cdot\left[\left(220 + 110\cdot\alpha_{ds1}\right)\cdot\exp\left(-\alpha_{ds2}\cdot\frac{f_{cm}}{f_{cmo}}\right)\right]\cdot10^{-6}\cdot\beta_{RH} = 0.000486$$

$k_h := 0.88$

Drying shrinkage: $\varepsilon_{cd} := k_h\cdot\varepsilon_{cd.0} = 0.000428$

$\varepsilon_{ca.t0} := 2.5\cdot\left(f_{ck} - 10\right)\cdot10^{-6} = 0.000063$

$\beta_{as.t} := 1 - \exp\left(-0.2\cdot t^{0.5}\right) = 1$

Autogenous shrinkage: $\varepsilon_{ca.t} := \varepsilon_{ca.t0}\cdot\beta_{as.t} = 0.000062$

Total shrinkage: $\varepsilon_{cs} := \varepsilon_{cd} + \varepsilon_{ca.t} = 0.00049$ (=0,49‰)

Appendix C - Minimum reinforcement

Conditions:

Concrete, B35

$f_{ctm} := 3.2MPa$ Mean tensile strength

Reinforcement

$f_{yk} := 500MPa$ Charachteristic strength

$c_{nom.s} := 25mm$ Cover to steel

$ø10 := 10mm$ Diametre of rebar

Slab

$span_x := 9m$ Length of span in x-direction

$span_y := 6m$ Length of span in y-direction

$h_{slab} := 200mm$ Slab thickness

$$d_x := h_{slab} - c_{nom.s} - \frac{ø10}{2} = 170 \cdot mm$$

Effective height off cross section in x-direction

$$d_y := h_{slab} - c_{nom.s} - ø10 - \frac{ø10}{2} = 160 \cdot mm$$

Effective height off cross section in y-direction

Minimum reinforcement:

(EC2-1-1: NA.9.2.1.1(1))

$$A_{s.min.x} := \max\left(0.26 \cdot \frac{f_{ctm}}{f_{yk}} \cdot span_y \cdot d_x, 0.0013 \cdot span_y \cdot d_x\right) = 1.697 \times 10^3 \cdot mm^2$$

$$A_{s.min.y} := \max\left(0.26 \cdot \frac{f_{ctm}}{f_{yk}} \cdot span_x \cdot d_y, 0.0013 \cdot span_x \cdot d_y\right) = 2.396 \times 10^3 \cdot mm^2$$

Maximum reinforcement:

(EC2-1-1: NA.9.2.1.1(3))

$$A_{s.max.x} := 0.04 \cdot span_y \cdot h_{slab} = 4.8 \times 10^4 \cdot mm^2$$

$$A_{s.max.y} := 0.04 \cdot span_x \cdot h_{slab} = 7.2 \times 10^4 \cdot mm^2$$

Maximum spacing:

(EC2-1-1: NA.9.3.1.1(3)) $s_{max.slabs.1} := \min(3 \cdot d_y, 400mm) = 400 \cdot mm$

In areas with concentrated loads / maximum moment:

$$s_{max.slabs.2} := \min(2 \cdot d_y, 250mm) = 250 \cdot mm$$

Reinforcement chosen due to requirements:

$A_{10} := \pi \cdot (5mm)^2 = 78.54 \cdot mm^2$ Cross-section area of ø10 rebar

Bottom:

x-direction:

$$s_{max.x} := \frac{A_{10} \cdot span_y}{A_{s.min.x}} = 277.644 \cdot mm$$

Maximum spacing allowed with ø10 in x-direction

y-direction:

$$s_{max.y} := \frac{A_{10} \cdot span_x}{A_{s.min.y}} = 294.996 \cdot mm$$

Maximum spacing allowed with ø10 in y-direction

Chooses mesh of ø10 cc270 in both directions in bottom

Top, over columns:

50% of reinforcement in top is placed within 0,125*span to each side of the column.

x-direction:

$$N_{x.top} := \frac{A_{s.min.x}}{A_{10}} = 21.61$$

Minimum rebars in x-direction

Chooses 22ø10 over column in x-direction

y-direction:

$$N_{y.top} := \frac{A_{s.min.y}}{A_{10}} = 30.509$$

Minimum rebars in y-direction

Chooses 31ø10 over column in y-direction

Appendix D - Load balancing

$A_p := 150mm^2$	Area of tendon
$k_1 := 0.8$	Coefficient, clause EC2-1-1: 5.10.2.1(1)P
$k_2 := 0.9$	Coefficient, clause EC2-1-1: 5.10.2.1(1)P
$f_{pk} := 1860MPa$	Nominal strength of tendon
$f_{p0.1k} := 1670MPa$	Nominal yield strength of tendon
$\sigma_{p.max} := \min\left(k_1 \cdot f_{pk}, k_2 \cdot f_{p0.1k}\right) = 1.488 \times 10^3 \cdot MPa$	Maximum stress applied to tendon clause: EC2-1-1: 5.10.2.1(1)P
$P_{max} := A_p \cdot \sigma_{p.max} = 223.2 \cdot kN$	Maximum jacking force
$P_{mt} := 0.8 \cdot P_{max} = 178.56 \cdot kN$	Effective prestressing force due to total losses when assumed a total of 20% loss
$h_{slab} := 200mm$	Slab thickness
$G_k := h_{slab} \cdot 25 \frac{kN}{m^3} = 5 \cdot \frac{kN}{m^2}$	Characteristic dead load
$span_x := 9m$	Span in x-direction
$span_y := 6m$	Span in y-direction
$q_{bal.x} := 0.7G_k \cdot 2 \cdot span_y = 42 \cdot \frac{kN}{m}$	Load to be balanced in x-direction when assuming that 70% of the dead load should be balanced
$q_{bal.y} := 0.7G_k \cdot 3 \cdot span_x = 94.5 \cdot \frac{kN}{m}$	Load to be balanced in y-direction when assuming that 70% of the dead load should be balanced

$c_{nom.s} := 25mm$ Cover to reinforcement

$ø10 := 10mm$ Diameter of rebars

$d_{p2} := 20mm$ Diameter of tube surrounding tendons

$$h := 1.5\left(\frac{h_{slab}}{2} - c_{nom.s} - 2\cdot ø10 - \frac{d_{p2}}{2}\right) = 0.068\,m$$ Drape for idealized parabolic model

$$P_{req.x} := \frac{q_{bal.x}\cdot span_x^{\;2}}{8\cdot h} = 6.3\times 10^3\cdot kN$$ Required prestressing force in x-direction

$$P_{req.y} := \frac{q_{bal.y}\cdot span_y^{\;2}}{8\cdot h} = 6.3\times 10^3\cdot kN$$ Required prestressing force in y-direction

$$N_{req.x} := \frac{P_{req.x}}{P_{mt}} = 35.282$$ Required number of tendons in x-direction to balance 70% of dead load

$$N_{req.y} := \frac{P_{req.y}}{P_{mt}} = 35.282$$ Required number of tendons in y-direction to balance 70% of dead load

$$\sigma_x := \frac{N_{req.x}\cdot P_{mt}}{h_{slab}\cdot 2\cdot span_y} = 2.625\cdot MPa$$ Prestress due to gross section in x-direction

$$\sigma_y := \frac{N_{req.y}\cdot P_{mt}}{h_{slab}\cdot 3\cdot span_x} = 1.167\cdot MPa$$ Prestress due to gross section in y-direction

Comment:

- Prestress in x-direction is above 2 MPa, and hence it correspond to an expected uneconomical design. The amount of the dead load to be balanced in x-direction is changed to 50% to meet te suggestion of not exceeding 2 MPa.

- Prestress in y-direction are quite low, though it meets the requirements for an economichal design. The amount of dead load to be balanced in y-direction is kept at 70%

$$q_{bal.x} := 0.5G_k \cdot 2 \cdot span_y = 30 \cdot \frac{kN}{m}$$

Load to be balanced in x-direction when assuming that 50% of the dead load should be balanced

$$P_{req.x} := \frac{q_{bal.x} \cdot span_x^{\,2}}{8 \cdot h} = 4.5 \times 10^3 \cdot kN$$

Required prestressing force in x-direction

$$N_{req.x} := \frac{P_{req.x}}{P_{mt}} = 25.202$$

Required number of tendons in x-direction to balance 50% of dead load

$$N_{req.y} := \frac{P_{req.y}}{P_{mt}} = 35.282$$

Required number of tendons in y-direction to balance 70% of dead load

$$N_x := 24$$

Chosen number of tendons in x-direction

$$N_y := 34$$

Chosen number of tendons in y-direction

$$\sigma_x := \frac{N_x \cdot P_{mt}}{h_{slab} \cdot 2 \cdot span_y} = 1.786 \cdot MPa$$

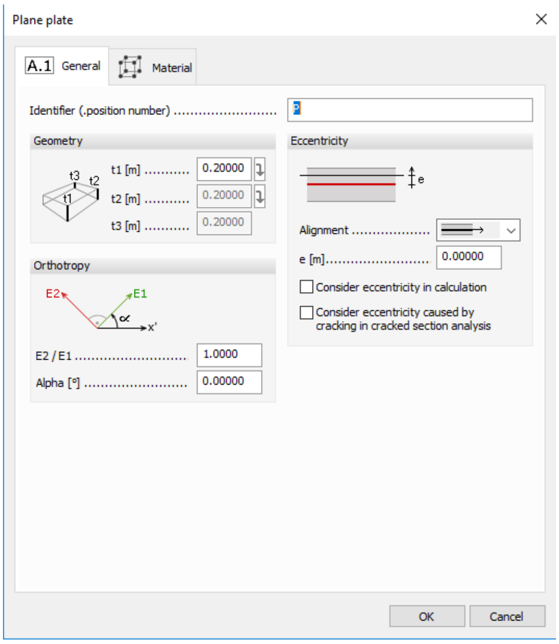
Prestress due to gross section in x-direction

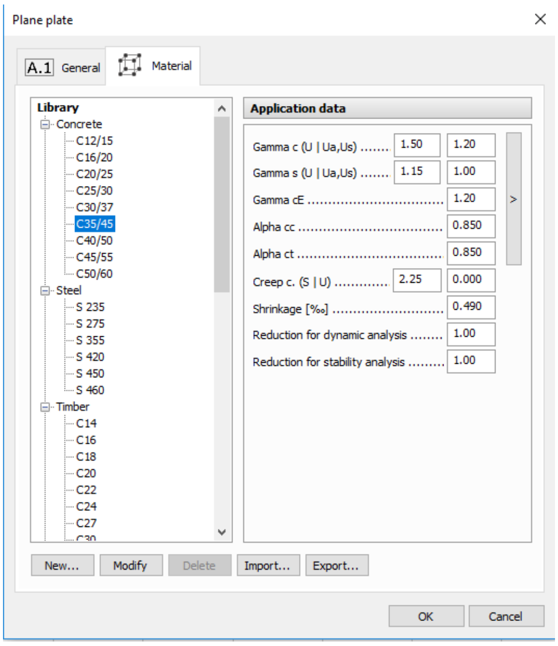
$$\sigma_y := \frac{N_y \cdot P_{mt}}{h_{slab} \cdot 3 \cdot span_x} = 1.124 \cdot MPa$$

Prestress due to gross section in y-direction

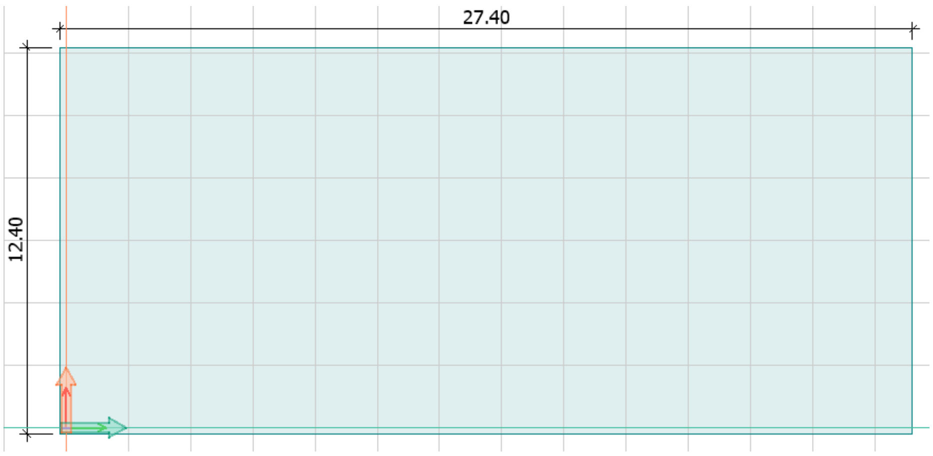
Appendix E - Modelling progress in FEM-Design 17

Choosing slab thickness 200 mm, B35 concrete, and creep/shrinkage coefficients:

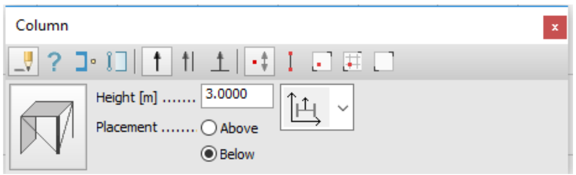


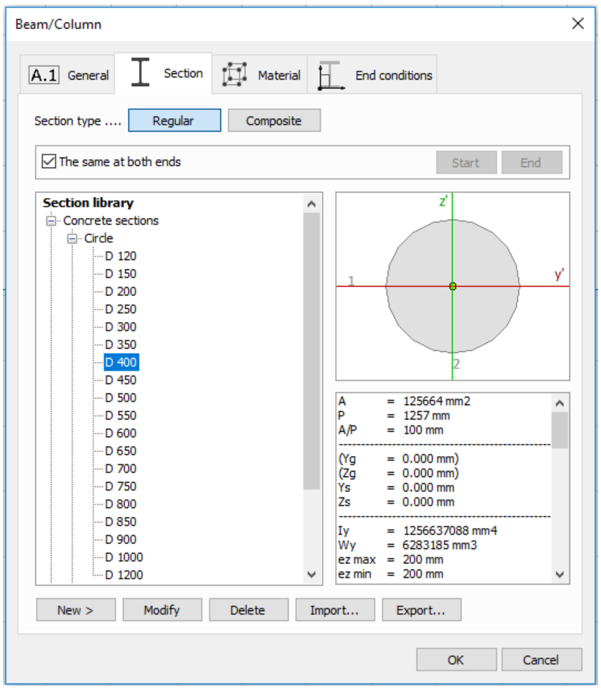


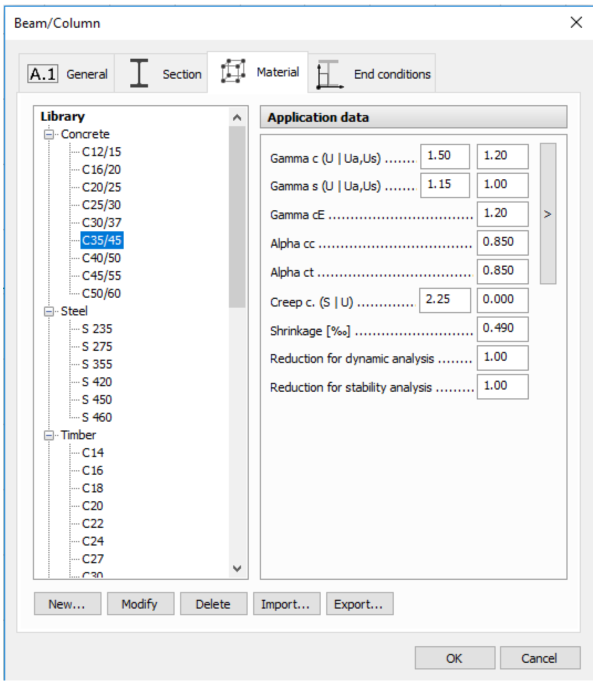
Drawing slab: (dimensions in metres)

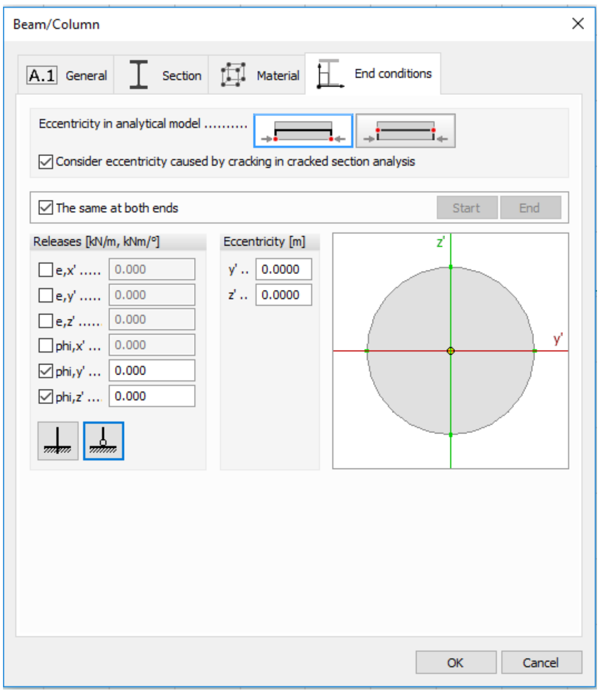


Choosing circular columns with diameter off 400 mm, height off 3m, B35, and hinged releases applied at the ends of theoretical axes:

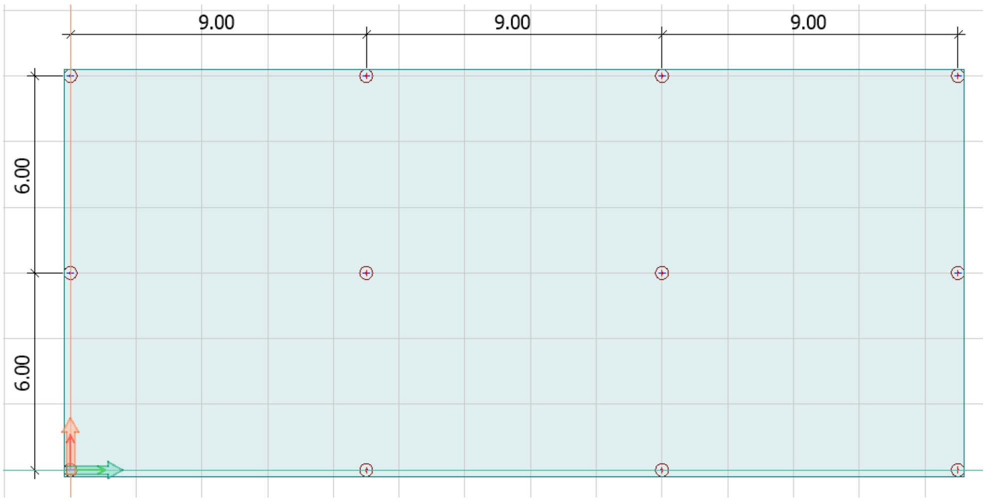




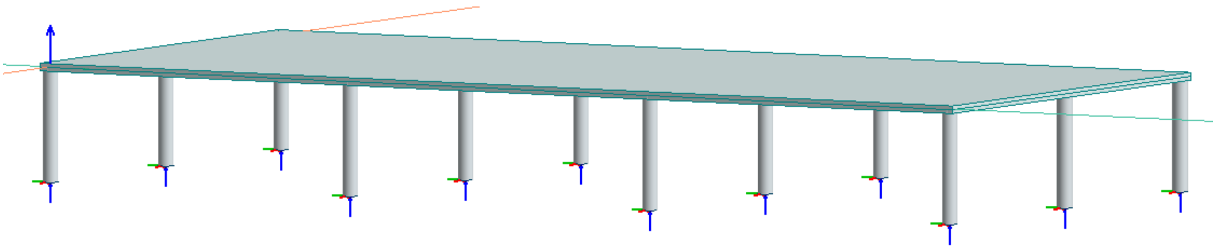




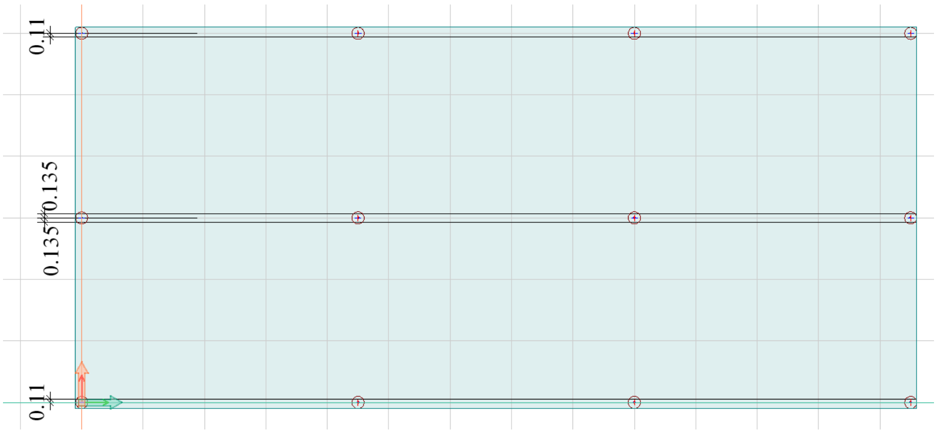
Drawing columns:



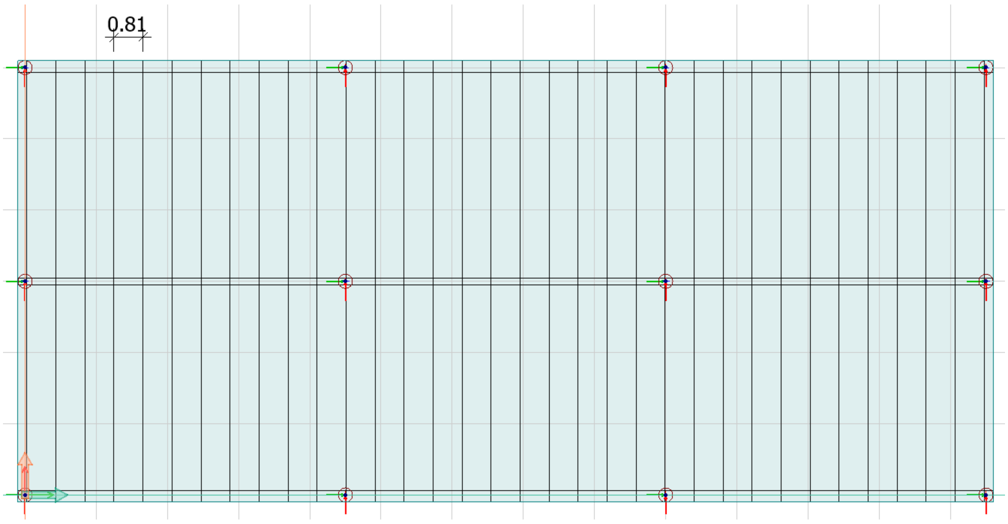
Adding hinged supports at column ends:



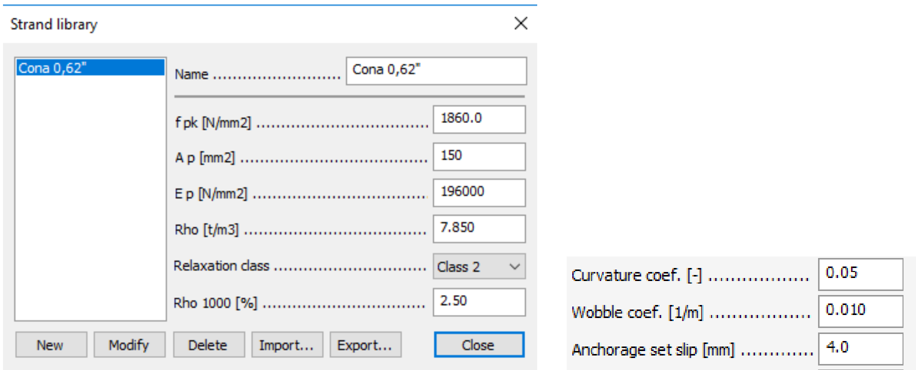
Placing lines in x-direction for placing of concentrated tendons. The lines represent the centre lines of the tendons for an idealized placement. The distances are chosen by assuming that maximum four tendons will be banded together, and that the spacing between the different groups of tendons will be 100 mm. (dimensions on figure is in metres)



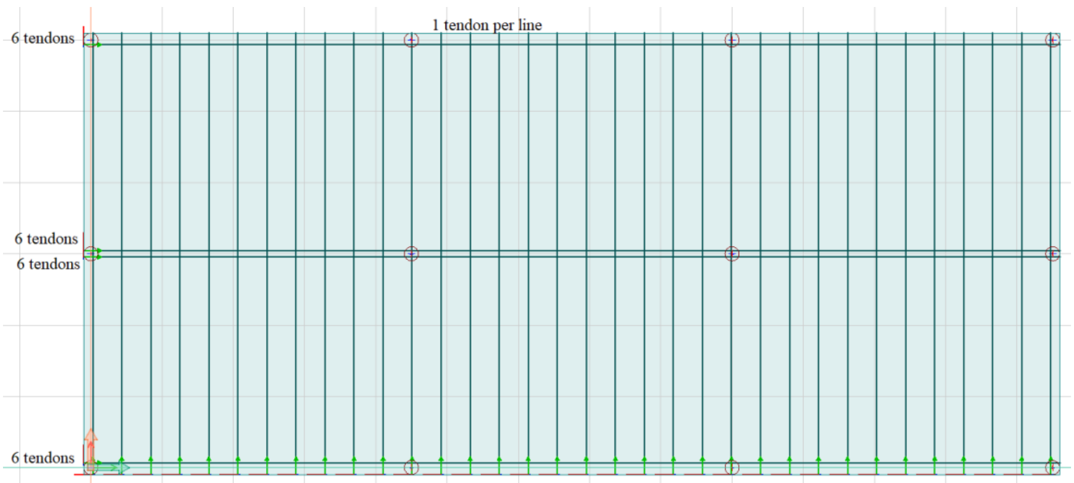
Placing lines in y-direction where tendons will be placed: (spacing is 815mm)



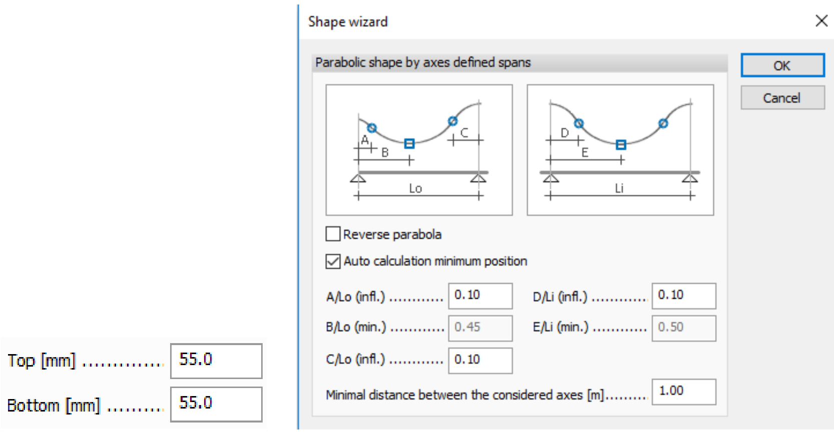
Choosing strand properties:



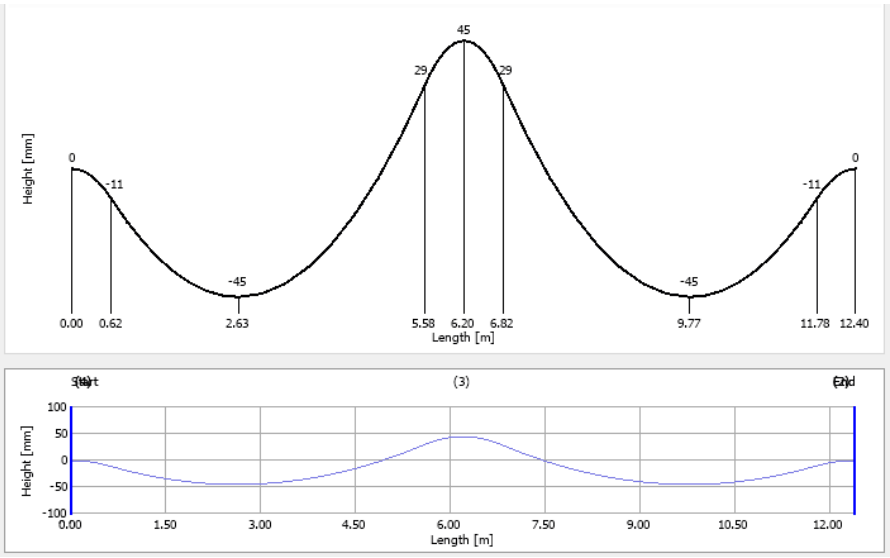
Tendon layout:



Tendon profiles are determined by a function called shape wizard. To use this function, axes are placed through the columns in both directions, these tells the wizard where the tendons should have maximum eccentricity in top. The minimum distance from the top and bottom surface of the slab to the centre of the tendon is also chosen, in addition to choosing the ratio that selects the placement of inflection points and the placement of maximum eccentricity in bottom.

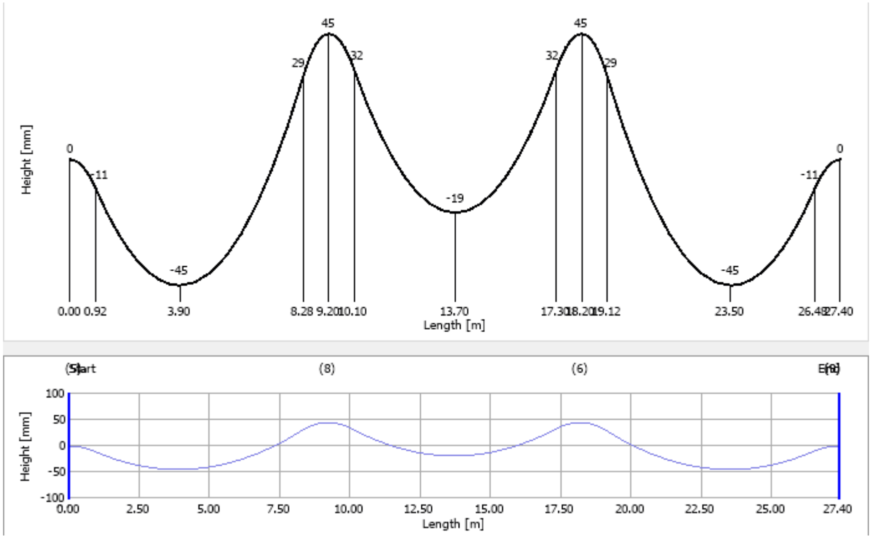


Tendon profiles in y-direction:

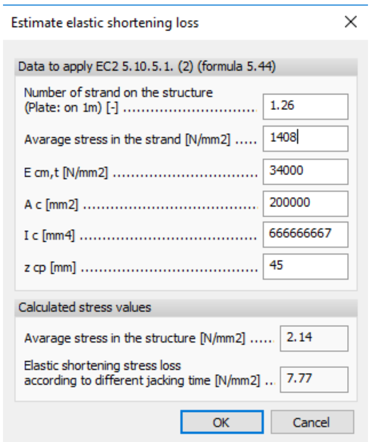


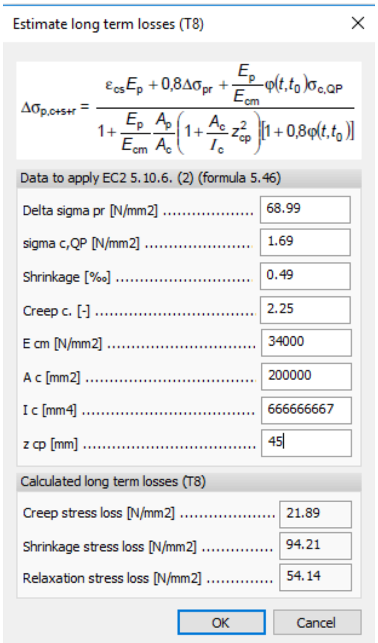
Tendon profiles in x-direction:

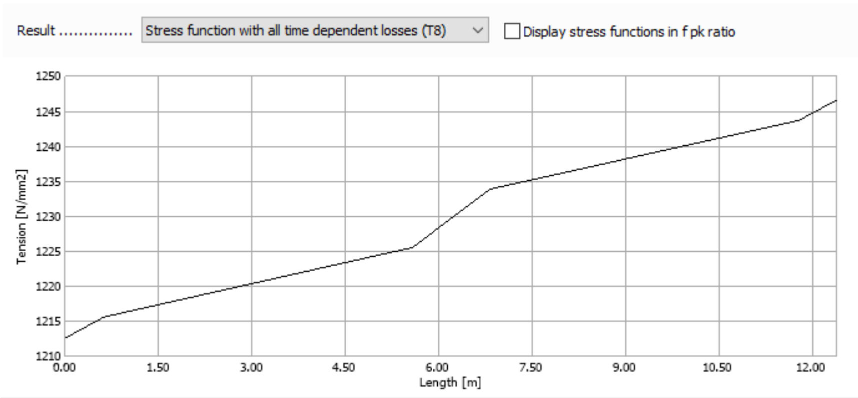
(The eccentricity in the mid span is adjusted manually to yield about the same equivalent force as the left and right span)



FEM-Design 17 can estimate the losses of prestress automatically. The following figures shows the losses for the tendons in y-direction:







Load cases are made. LL are live loads that is placed in different spans on the slab. The PTC T0 and PTC T8 load cases are the equivalent forces with respectively the initial prestress losses and all prestress losses included.

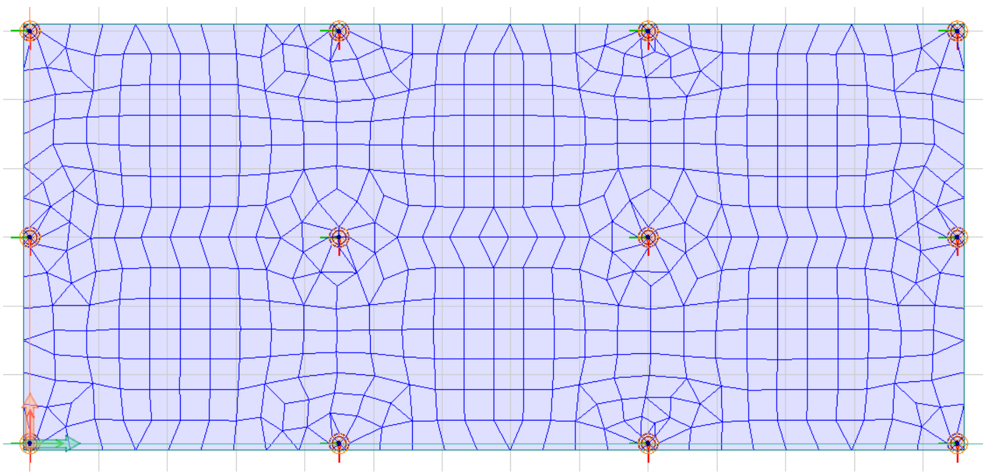
Load cases

No	Name	Type
1	Dead Load	+Struc. dead load
2	LL1	Ordinary
3	LL2	Ordinary
4	LL3	Ordinary
5	LL4	Ordinary
6	LL5	Ordinary
7	Shrinkage	+Shrinkage
8	PTC T0	Post tensioning
9	PTC T8	Post tensioning

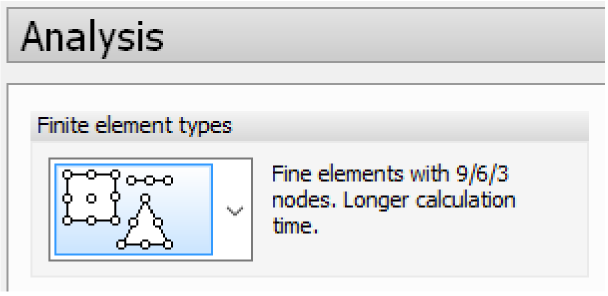
Load combinations

No	Name	Type	Factor	Included load ca
1	Initial	Sc	1.00	Dead Load
			1.00	PTC T0
2	Quasi-permanent	Sq	1.00	Dead Load
			0.30	LL1
			1.00	Shrinkage
			1.00	PTC T8
3	ULS1	U	1.20	Dead Load
			1.50	LL1
4	ULS2	U	1.20	Dead Load
			1.50	LL2
5	ULS3	U	1.20	Dead Load
			1.50	LL3
6	ULS4	U	1.20	Dead Load
			1.50	LL4
7	ULS5	U	1.20	Dead Load
			1.50	LL5

The slab is meshed automatically as shown in the following figure. A function called “peak smoothing” is used at column end points to avoid high valued peaks here in the analysis.

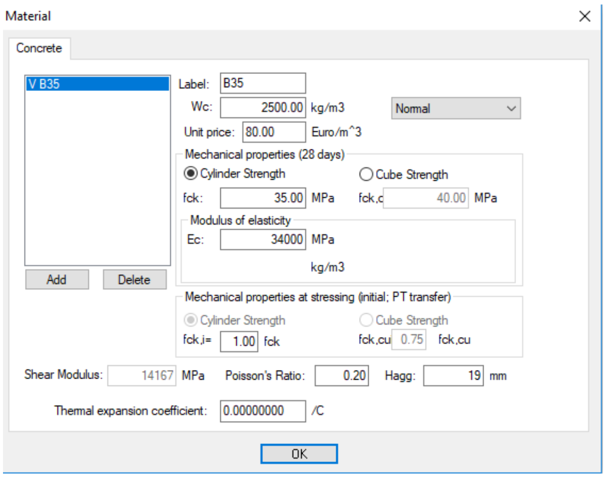


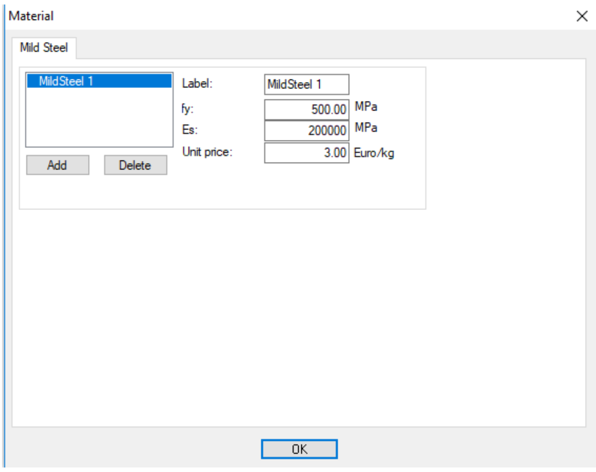
The analysis is done using fine elements:

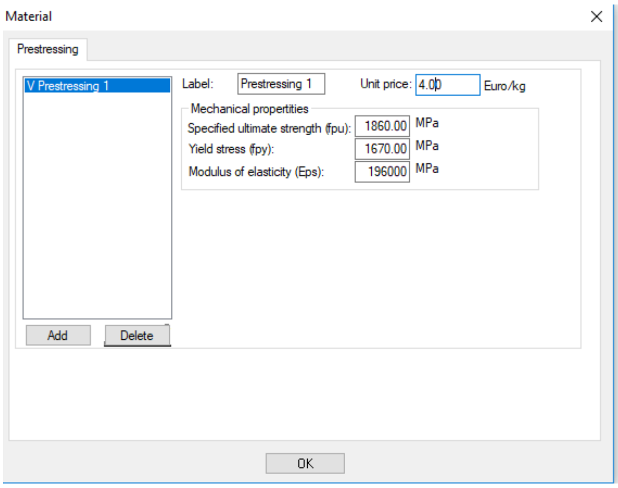


Appendix F - Modelling progress in ADAPT-Floor Pro

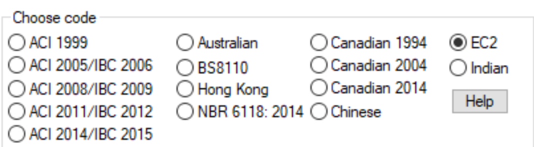
Defining material properties: (unit prices are neglected)

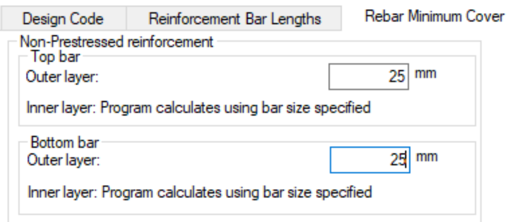


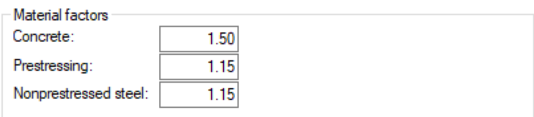


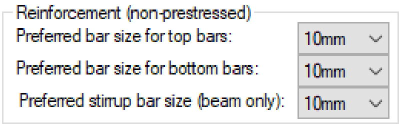


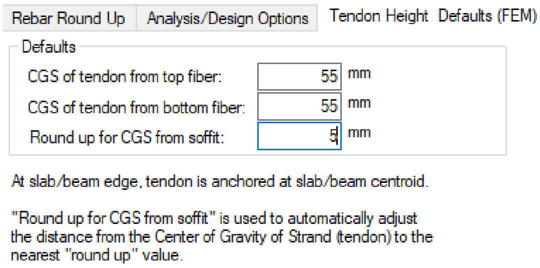
Choosing design criterias:



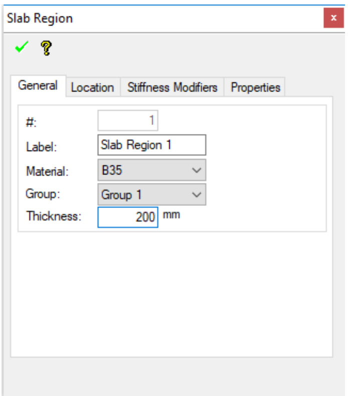




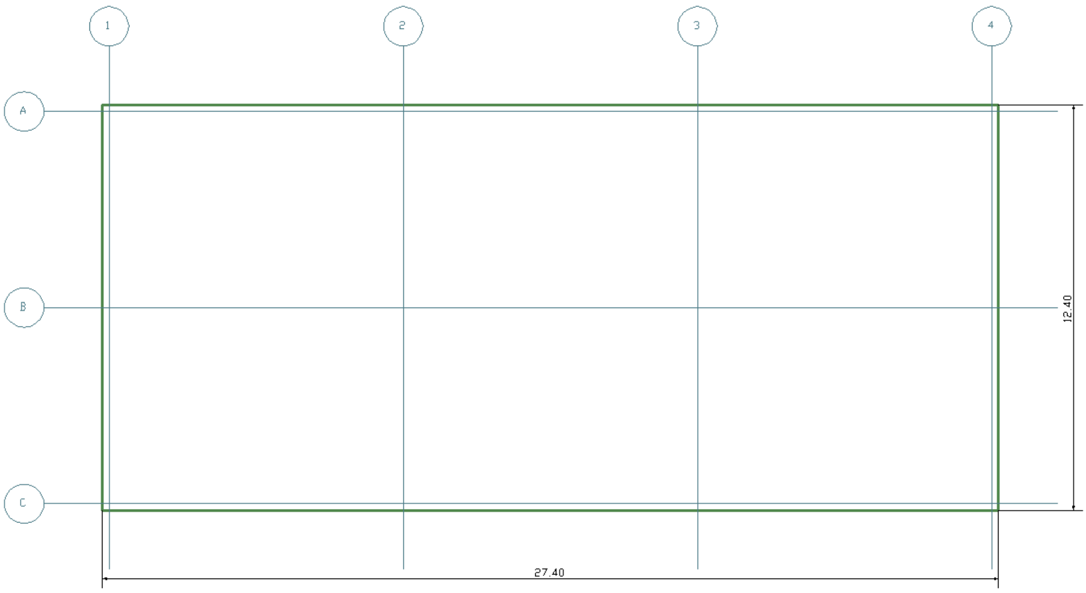




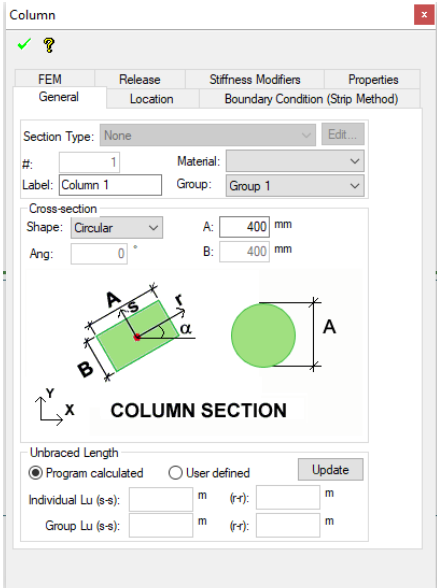
Choosing B35 concrete and slab thickness 200 mm:

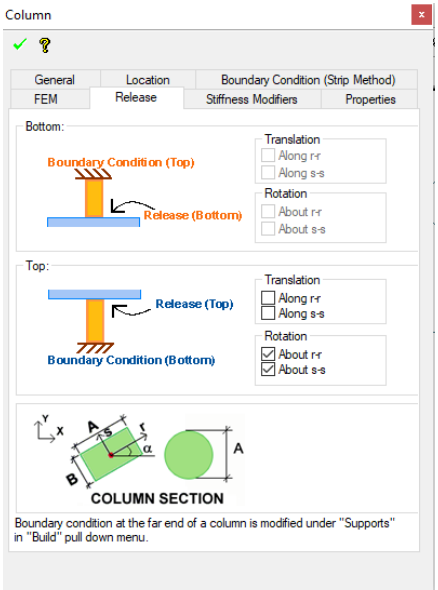


Creating gridlines and drawing slab region: (dimensions in metres)

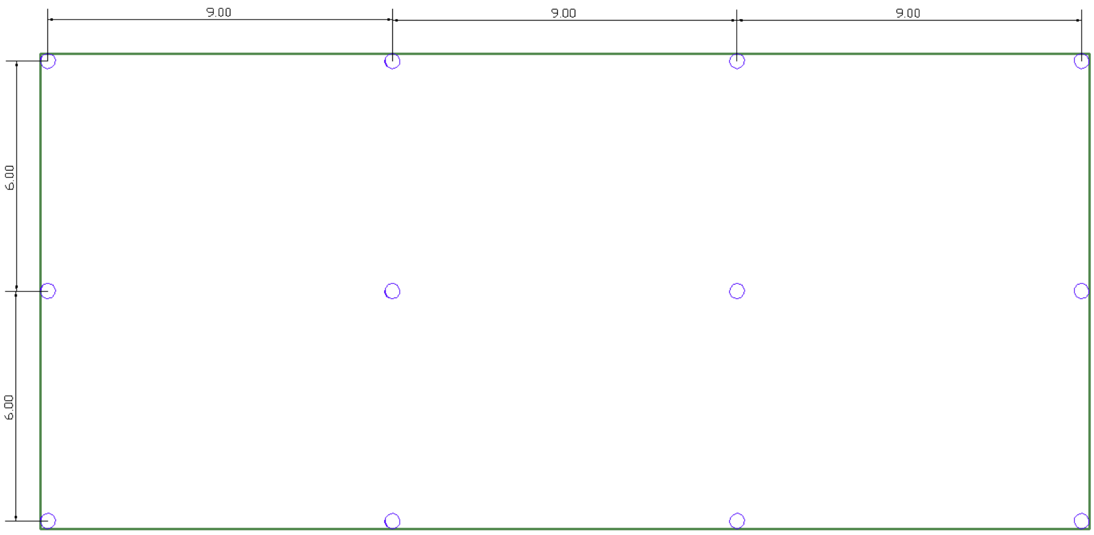


Choosing circular columns with diameter off 400 mm, with releases that are allowed to rotate:

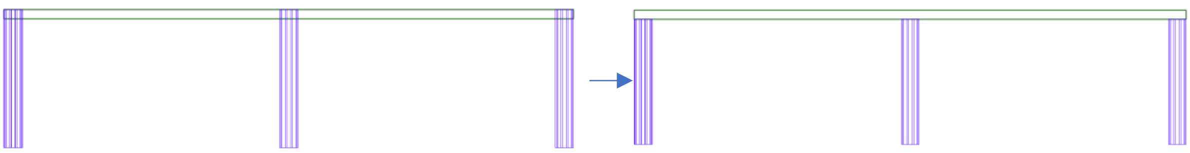




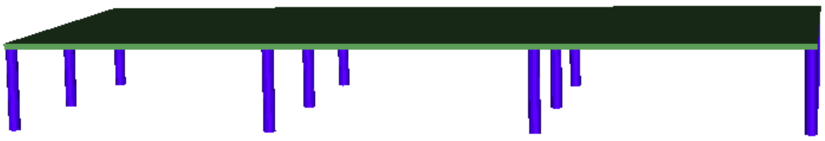
Modelling columns:



Establishing component connectivity:

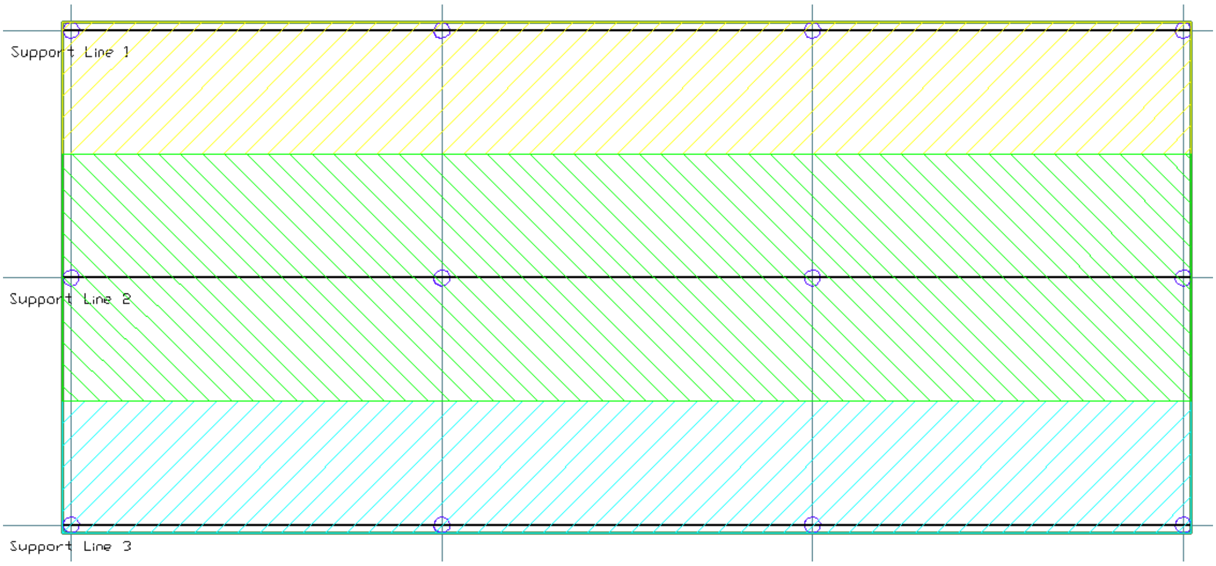


Model:

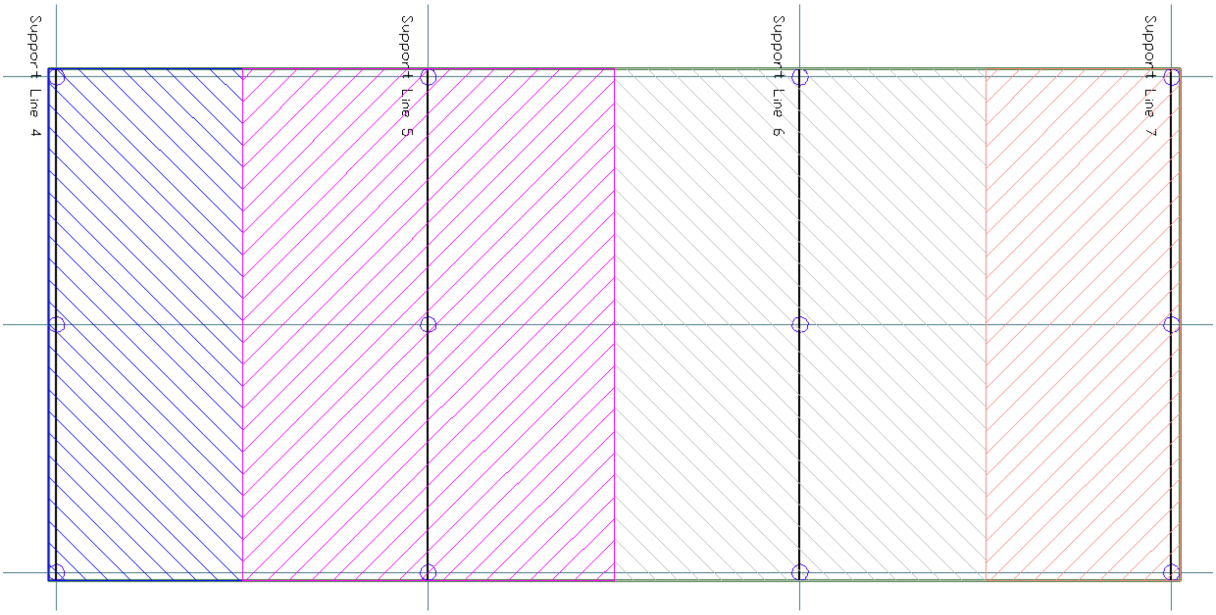


Creating support lines and design sections:

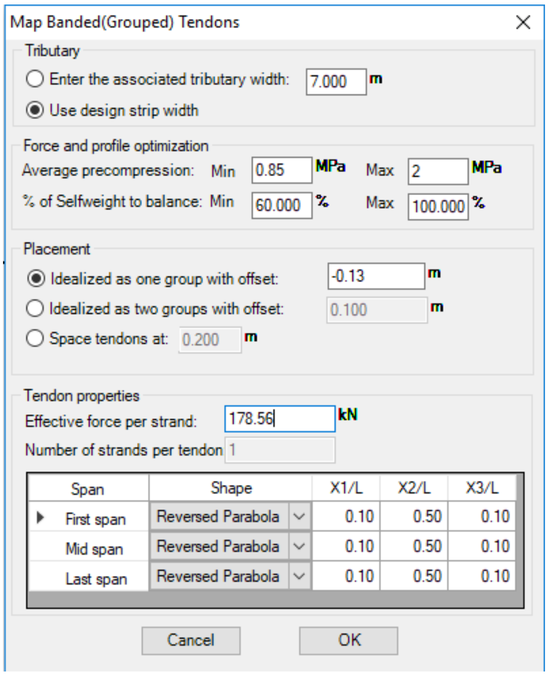
x-direction:

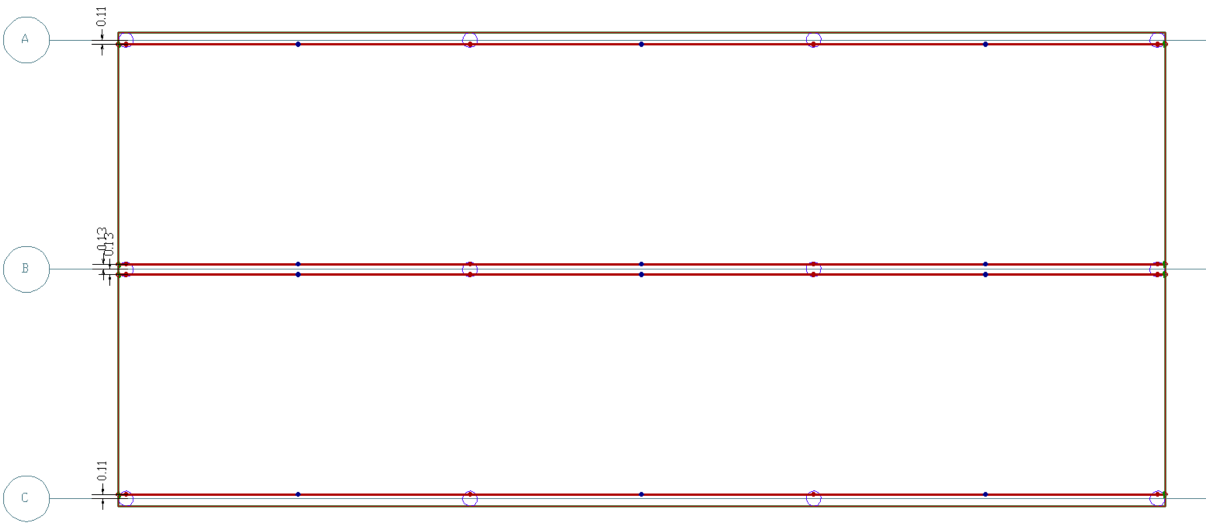


y-direction:

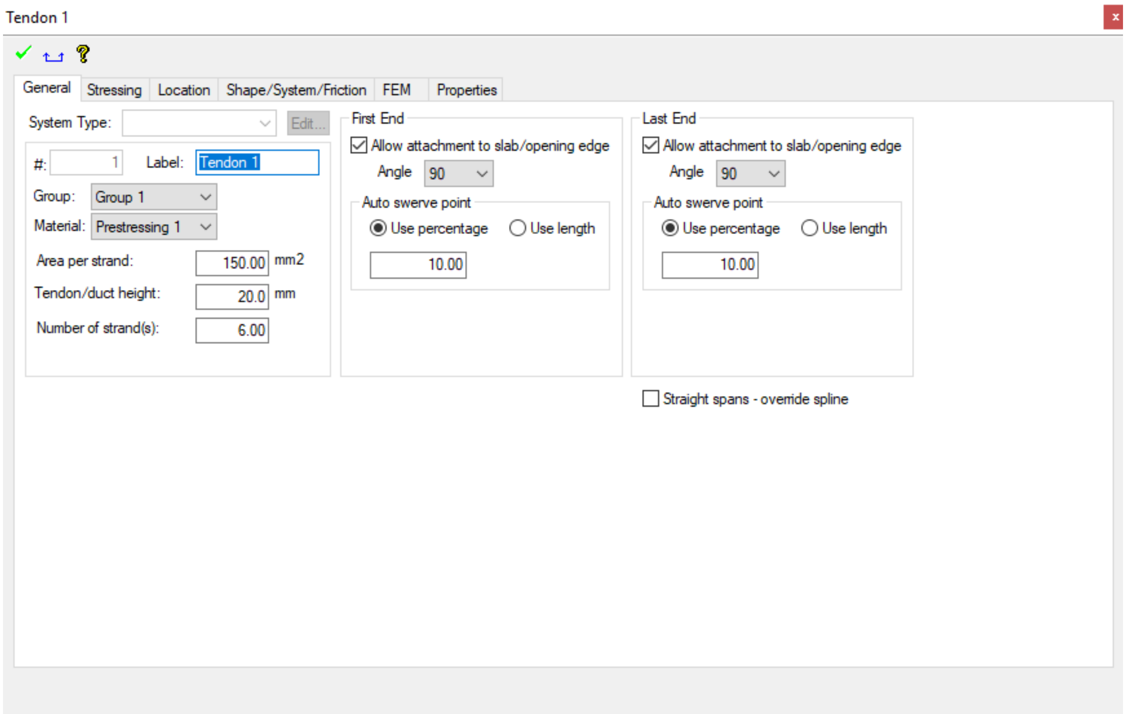


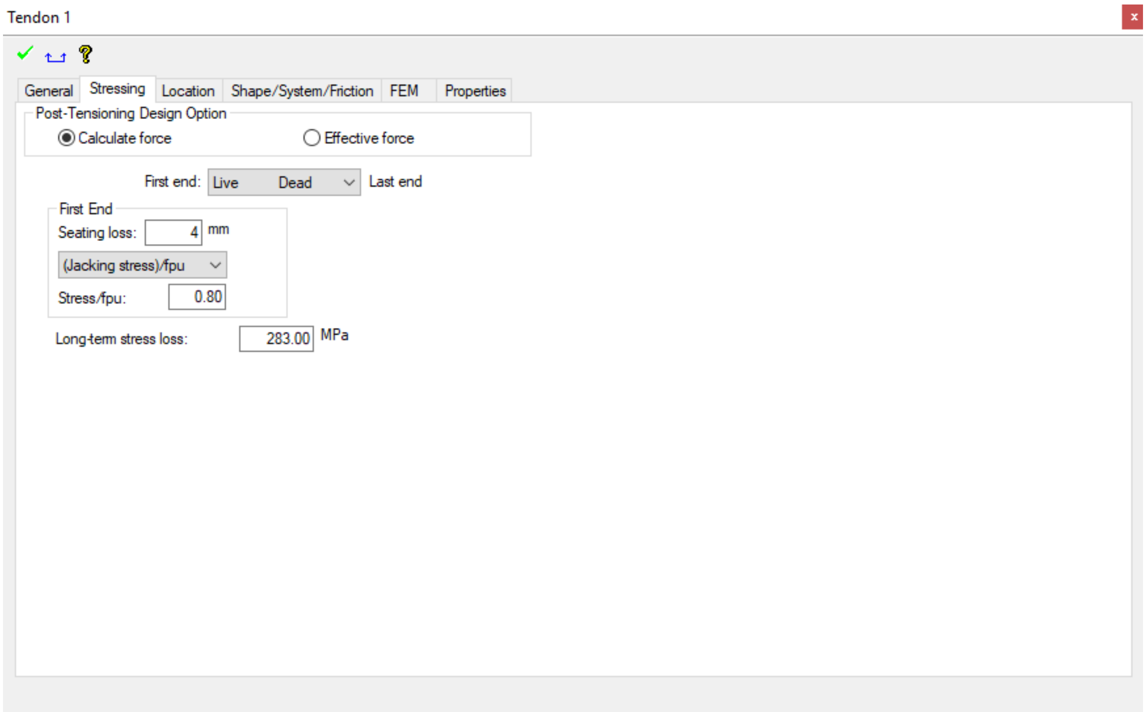
Placing tendons in x-direction. The tendon lines represent the centre lines of the tendons for an idealized placement. The distances are chosen by assuming that maximum four tendons will be banded together, and that the spacing between the different groups of tendons will be 100 mm. From the values given in the “Map Banded Tendons”-box, ADAPT will suggest the number and profile of tendons.

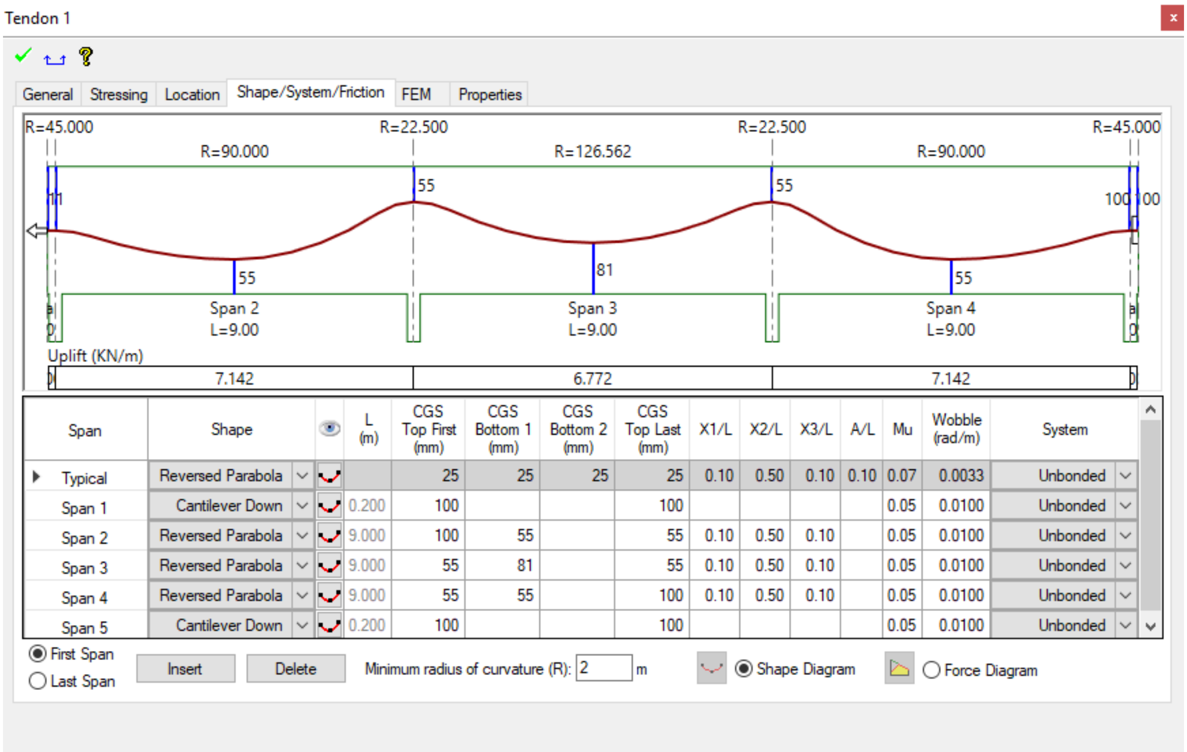




The number of tendons and profiles are changed. Adapt calculates initial losses of prestress, but long-term stress loss is added manually. The same values as calculated by FEM-Design is inserted:

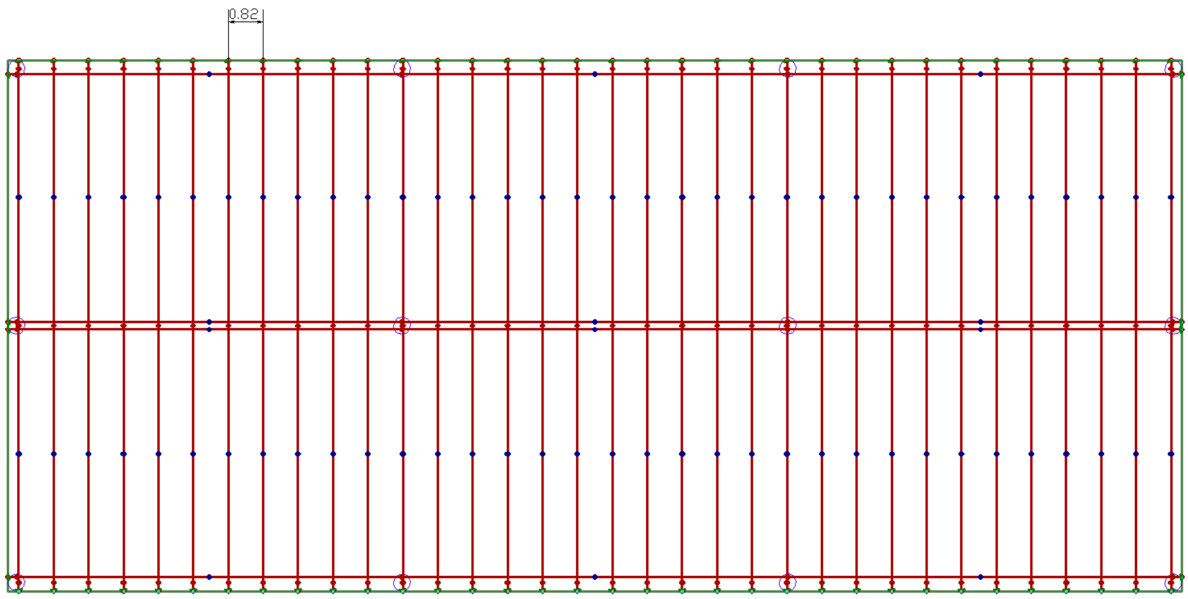


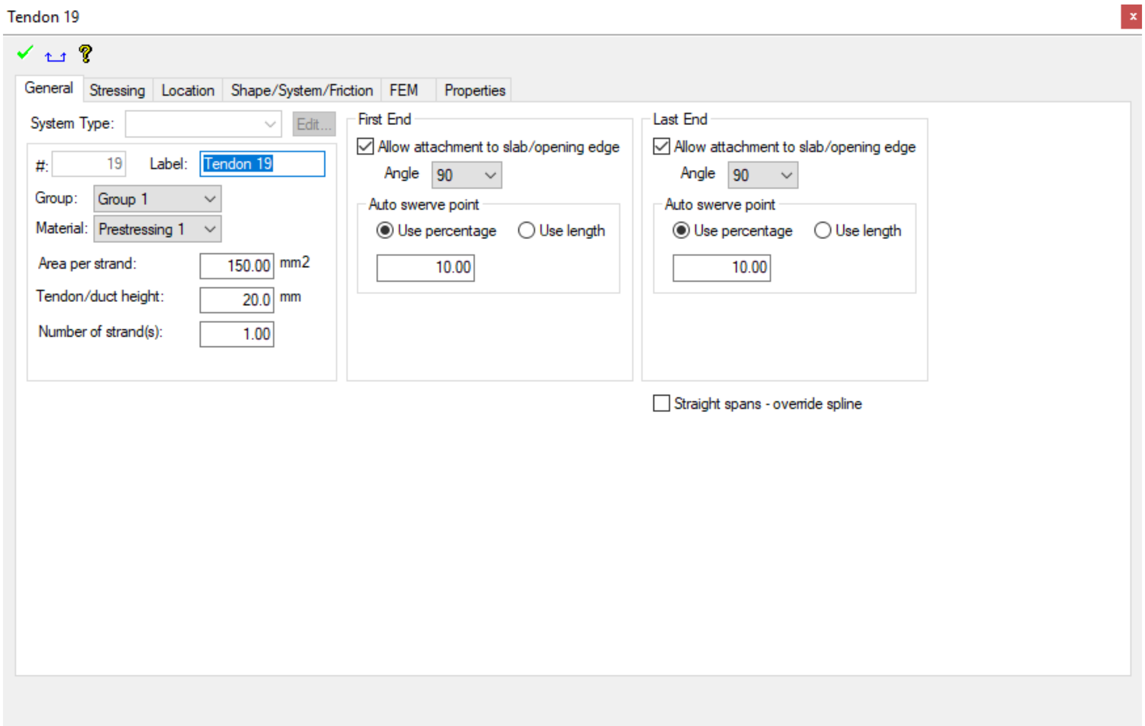


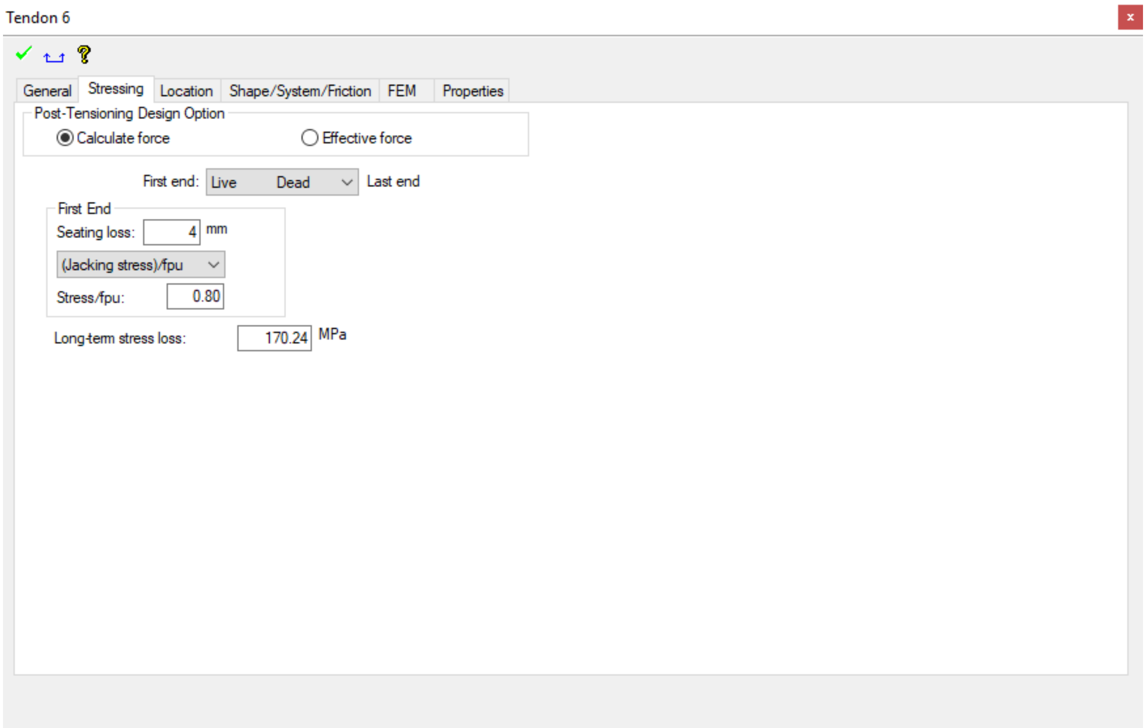


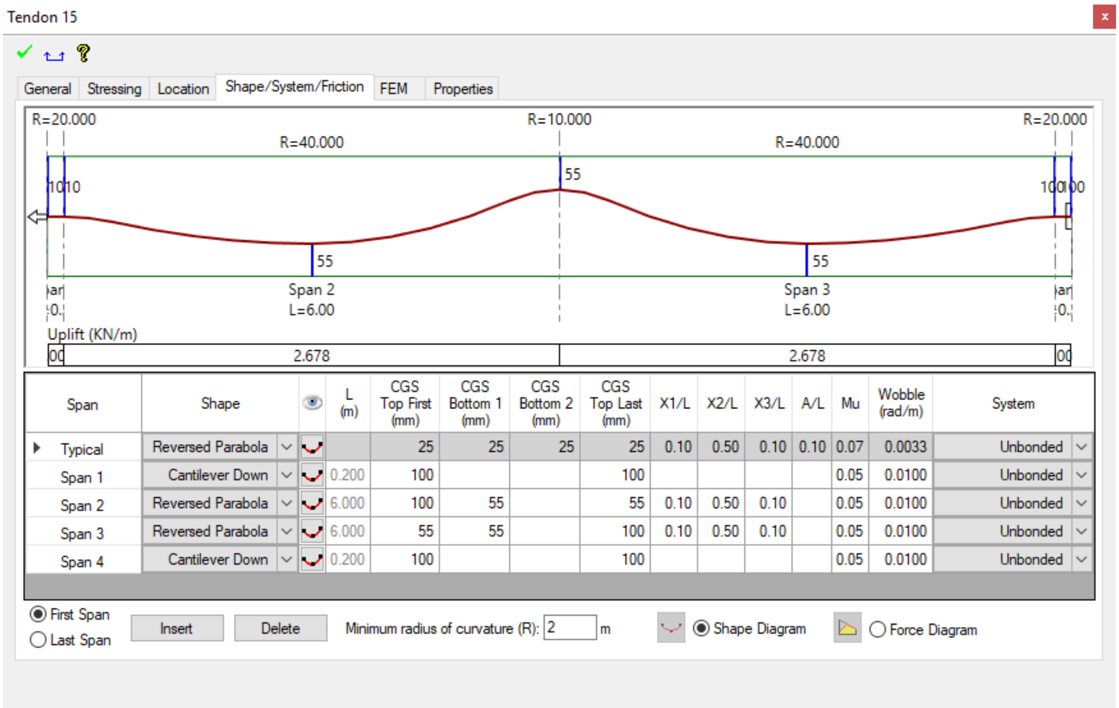
Span	Shape	L (m)	CGS Top First (mm)	CGS Bottom 1 (mm)	CGS Bottom 2 (mm)	CGS Top Last (mm)	X1/L	X2/L	X3/L	A/L	Mu	Wobble (rad/m)	System
Typical	Reversed Parabola		25	25	25	25	0.10	0.50	0.10	0.10	0.07	0.0033	Unbonded
Span 1	Cantilever Down	0.200	100			100					0.05	0.0100	Unbonded
Span 2	Reversed Parabola	9.000	100	55		55	0.10	0.50	0.10		0.05	0.0100	Unbonded
Span 3	Reversed Parabola	9.000	55	81		55	0.10	0.50	0.10		0.05	0.0100	Unbonded
Span 4	Reversed Parabola	9.000	55	55		100	0.10	0.50	0.10		0.05	0.0100	Unbonded
Span 5	Cantilever Down	0.200	100			100					0.05	0.0100	Unbonded

Placing tendons in y-direction: (spacing is 815mm)



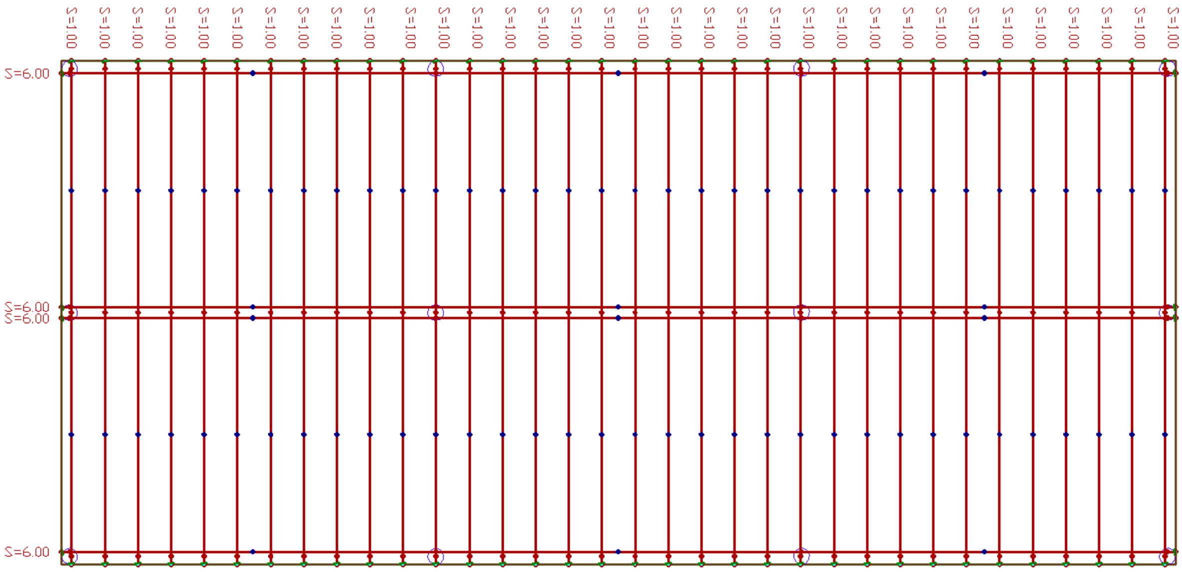

Tendon 19
General
Stressing
Location
Shape/System/Friction
FEM
Properties
System Type:
Edit...
#: 19
Label: Tendon 19
Group: Group 1
Material: Prestressing 1
Area per strand: 150.00 mm2
Tendon/duct height: 20.0 mm
Number of strand(s): 1.00
First End
Allow attachment to slab/opening edge
Angle 90
Auto swerve point
Use percentage
Use length
10.00
Last End
Allow attachment to slab/opening edge
Angle 90
Auto swerve point
Use percentage
Use length
10.00
Straight spans - override spline


Tendon 6
General
Stressing
Location
Shape/System/Friction
FEM
Properties
Post-Tensioning Design Option
Calculate force
Effective force
First end: Live Dead Last end
First End
Seating loss: 4 mm
(Jacking stress)/fpu
Stress/fpu: 0.80
Long-term stress loss: 170.24 MPa

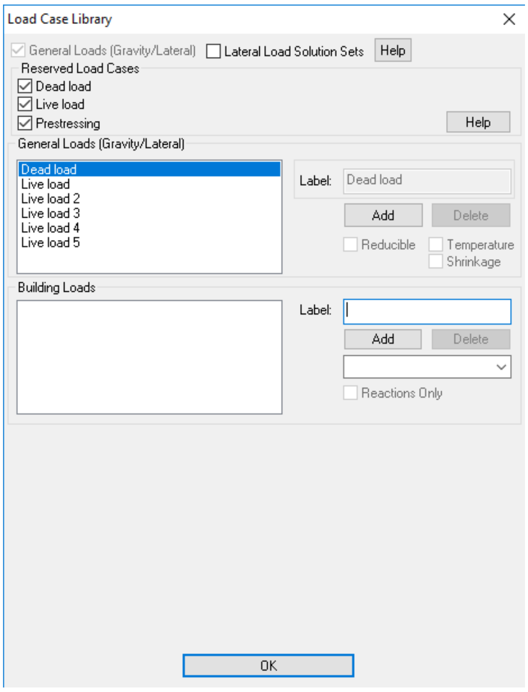


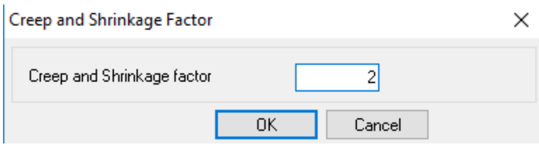
Span	Shape		L (m)	CGS Top First (mm)	CGS Bottom 1 (mm)	CGS Bottom 2 (mm)	CGS Top Last (mm)	X1/L	X2/L	X3/L	A/L	Mu	Wobble (rad/m)	System
Typical	Reversed Parabola			25	25	25	25	0.10	0.50	0.10	0.10	0.07	0.0033	Unbonded
Span 1	Cantilever Down		0.200	100			100					0.05	0.0100	Unbonded
Span 2	Reversed Parabola		6.000	100	55		55	0.10	0.50	0.10		0.05	0.0100	Unbonded
Span 3	Reversed Parabola		6.000	55	55		100	0.10	0.50	0.10		0.05	0.0100	Unbonded
Span 4	Cantilever Down		0.200	100			100					0.05	0.0100	Unbonded

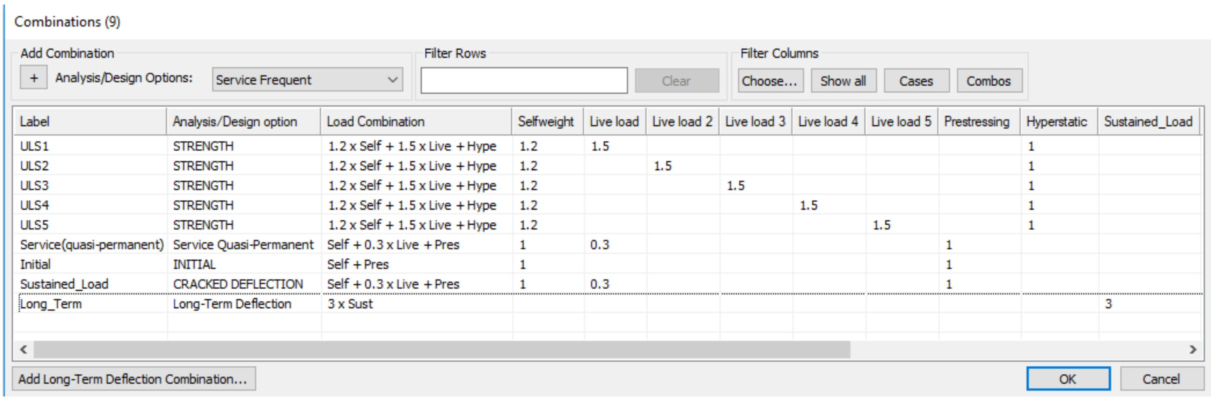
Tendon layout: (S is number of tendons represented by the lines)



Load cases are made. Different live loads have same values but are placed on different spans in the slab. For the quasi-permanent load combination where long-term effects are included, ADAPT uses a creep and shrinkage factor given by the American code.

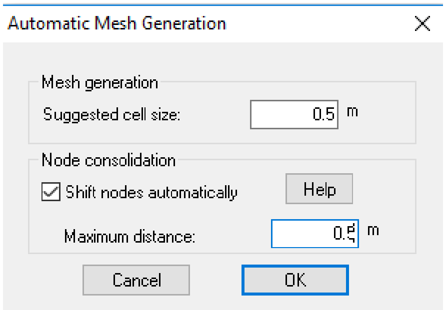


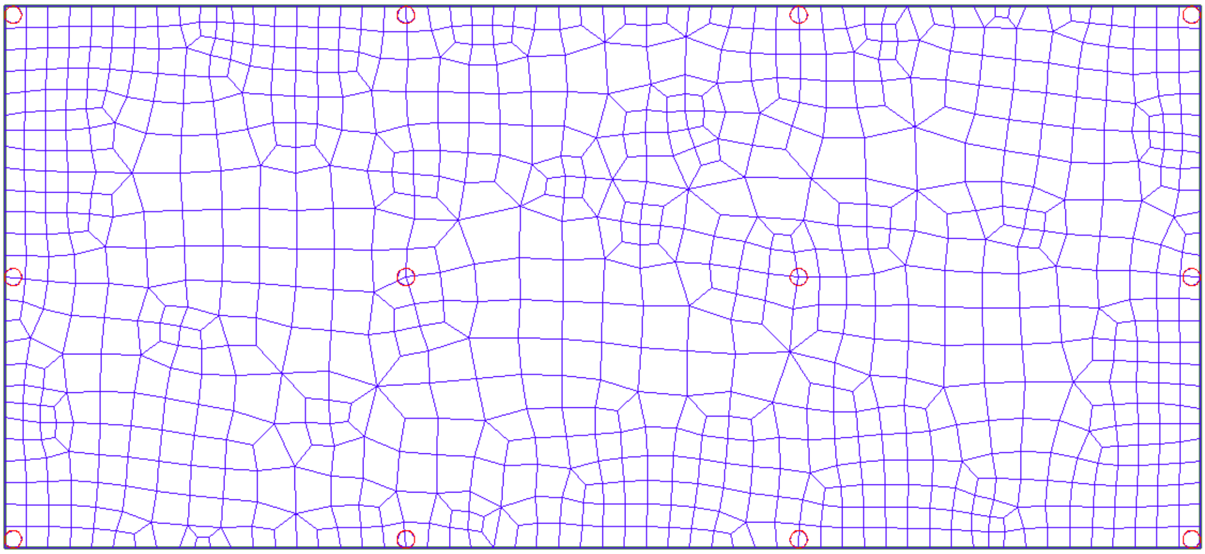




Label	Analysis/Design option	Load Combination	Selfweight	Live load	Live load 2	Live load 3	Live load 4	Live load 5	Prestressing	Hyperstatic	Sustained_Load
ULS1	STRENGTH	1.2 x Self + 1.5 x Live + Hype	1.2	1.5						1	
ULS2	STRENGTH	1.2 x Self + 1.5 x Live + Hype	1.2		1.5					1	
ULS3	STRENGTH	1.2 x Self + 1.5 x Live + Hype	1.2			1.5				1	
ULS4	STRENGTH	1.2 x Self + 1.5 x Live + Hype	1.2				1.5			1	
ULS5	STRENGTH	1.2 x Self + 1.5 x Live + Hype	1.2					1.5		1	
Service(quasi-permanent)	Service Quasi-Permanent	Self + 0.3 x Live + Pres	1	0.3					1		
Initial	INITIAL	Self + Pres	1						1		
Sustained_Load	CRACKED DEFLECTION	Self + 0.3 x Live + Pres	1	0.3					1		
Long_Term	Long-Term Deflection	3 x Sust									3

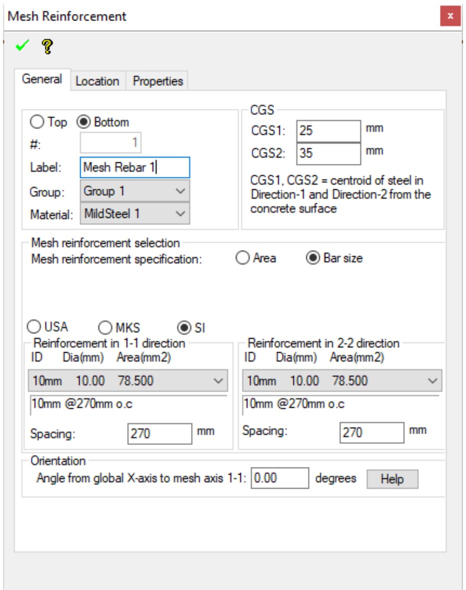
Generating mesh. Suggested cell size is changed so that each span contains a minimum of 10 cells:

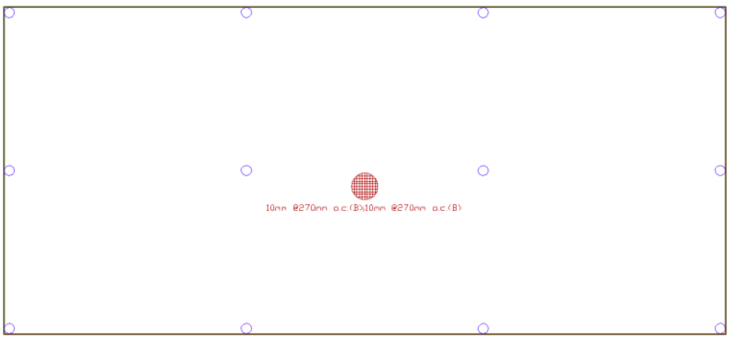




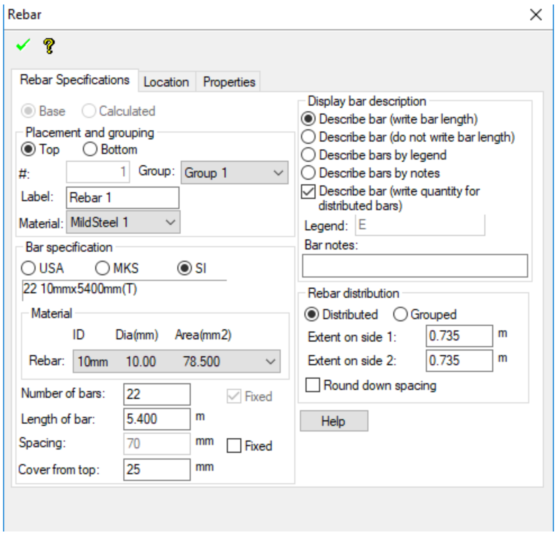
Minimum reinforcement is added to the structure:

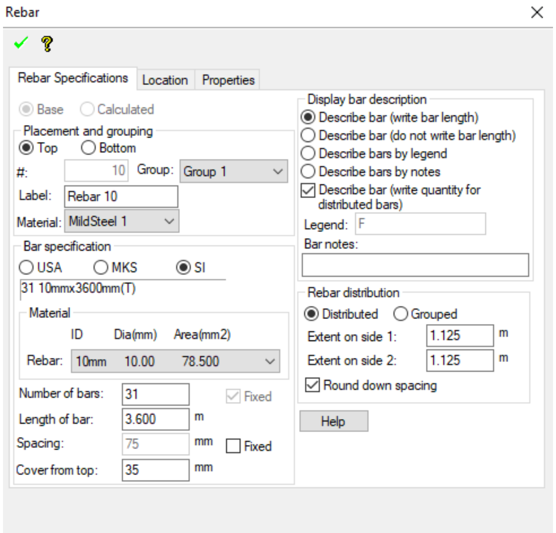
Bottom:

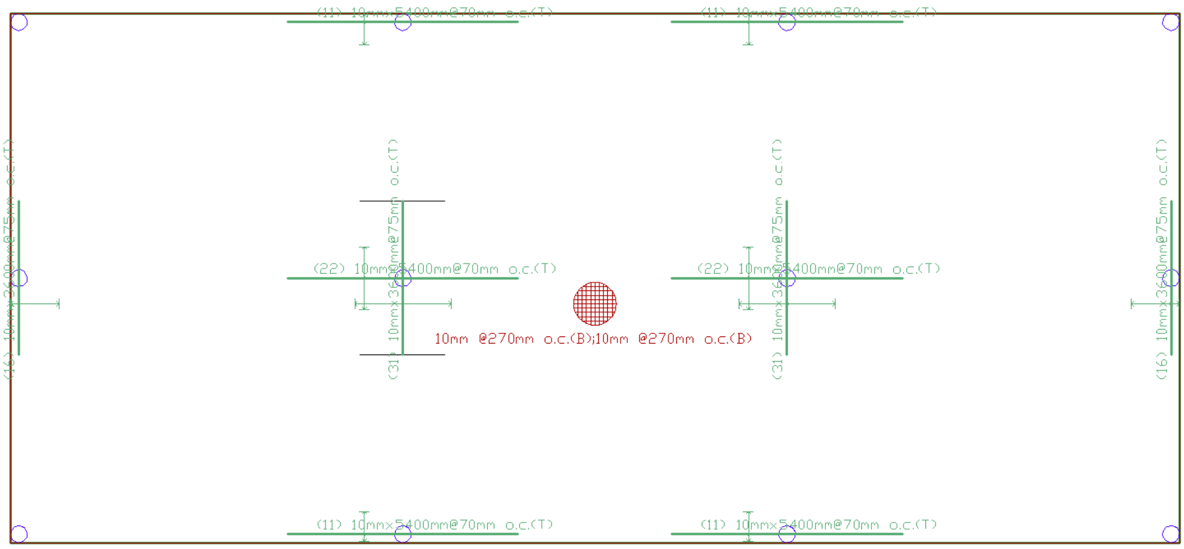




Top:


Rebar
Rebar Specifications
Location
Properties
Base
Calculated
Placement and grouping
Top
Bottom
#: 1
Group: Group 1
Label: Rebar 1
Material: MildSteel 1
Bar specification
USA
MKS
SI
22 10mmx5400mm(T)
Material
ID Dia(mm) Area(mm2)
Rebar: 10mm 10.00 78.500
Number of bars: 22
Fixed
Length of bar: 5.400 m
Spacing: 70 mm
Fixed
Cover from top: 25 mm
Display bar description
Describe bar (write bar length)
Describe bar (do not write bar length)
Describe bars by legend
Describe bars by notes
Describe bar (write quantity for distributed bars)
Legend: E
Bar notes:
Rebar distribution
Distributed
Grouped
Extent on side 1: 0.735 m
Extent on side 2: 0.735 m
Round down spacing
Help


Rebar
Rebar Specifications
Location
Properties
Base
Calculated
Placement and grouping
Top
Bottom
#: 10
Group: Group 1
Label: Rebar 10
Material: MildSteel 1
Bar specification
USA
MKS
SI
31 10mmx3600mm(T)
Material
ID Dia(mm) Area(mm2)
Rebar: 10mm 10.00 78.500
Number of bars: 31
Fixed
Length of bar: 3.600 m
Spacing: 75 mm
Fixed
Cover from top: 35 mm
Display bar description
Describe bar (write bar length)
Describe bar (do not write bar length)
Describe bars by legend
Describe bars by notes
Describe bar (write quantity for distributed bars)
Legend: F
Bar notes:
Rebar distribution
Distributed
Grouped
Extent on side 1: 1.125 m
Extent on side 2: 1.125 m
Round down spacing
Help


(11) 10mmx5400mm@70mm o.c.(T)
(22) 10mmx5400mm@70mm o.c.(T)
(31) 10mmx3600mm@75mm o.c.(T)
(16) 10mmx3600mm@75mm o.c.(T)
10mm @270mm o.c.(B);10mm @270mm o.c.(B)

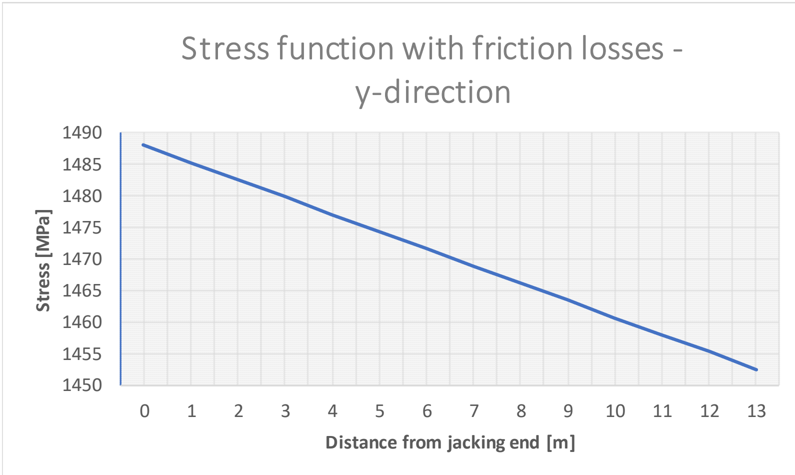
Appendix G - Losses of prestress

Due to friction, EC2-1-1 clause 5.10.5.2

$A_p := 150mm^2$	Area of tendon
$f_{pk} := 1860MPa$	Nominal strength of tendon
$P_{max} := 0.8f_{pk} \cdot A_p = 223.2 \cdot kN$	Maximum prestressing force per tendon
$k := 0.01 \cdot \frac{1}{m}$	Wobble coefficient
$\mu := 0.05$	Friction coefficient
$L_x := 27.4m$	Length of slab in x-direction
$L_y := 12.4m$	Length of slab in y-direction

y-direction:

$\theta_y := 0.33599$	Sum of angular displacements. Calculations are shown in Appendix H
$x := L_y$	Distance to point with maximum friction
$\Delta P_{\mu.y} := P_{max} \cdot \left[1 - e^{\left[-\mu \cdot \left(\theta_y + k \cdot x\right)\right]}\right] = 5.075 \cdot kN$	Loss of prestressing force due to friction in point x.
$\Delta\sigma_{\mu.y} := \frac{\Delta P_{\mu.y}}{A_p} = 33.833 \cdot MPa$	Loss of stress due to friction in point x.



x-direction:

$\theta_x := 0.33978$ Sum of angular displacements. Calculations are shown in Appendix H

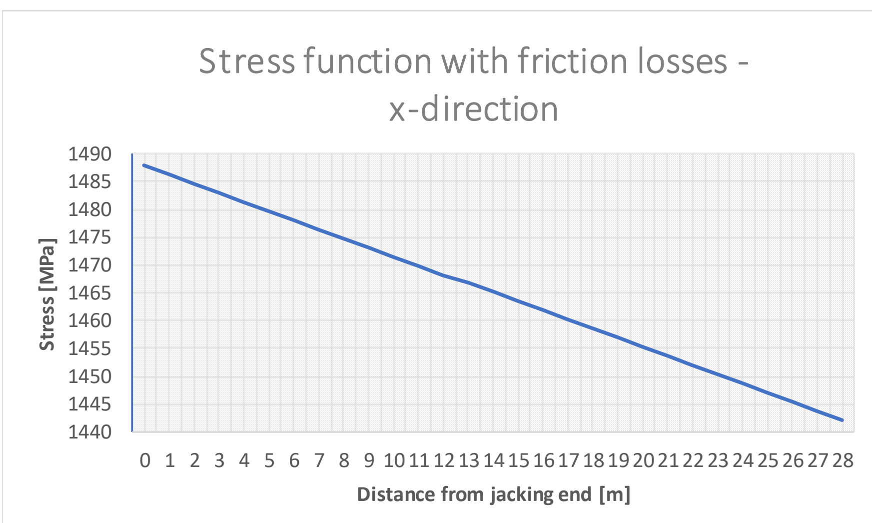
$x := L_x$ Distance to point with maximum friction

$$\Delta P_{\mu.x} := P_{max} \cdot \left[1 - e^{\left[-\mu \cdot \left(\theta_x + k \cdot x \right) \right]} \right] = 6.746 \cdot kN$$

Loss of prestressing force due to friction in point x.

$$\Delta\sigma_{\mu.x} := \frac{\Delta P_{\mu.x}}{A_p} = 44.972 \cdot MPa$$

Loss of stress due to friction in point x.



Due to anchorage set slip, EC2-1-1 clause 5.10.5.3

$\Delta slip := 4mm$ Anchorage slip

$E_p := 196GPa$ Mean elastic modulus of tendon

y-direction:

$$\beta_y := \frac{\Delta P_{\mu.y}}{L_y} = 0.409 \cdot \frac{kN}{m}$$

Slope of the friction loss line

$$L_{d.y} := \sqrt{\frac{(\Delta slip \cdot E_p \cdot A_p)}{\beta_y}} = 16.951\,m$$

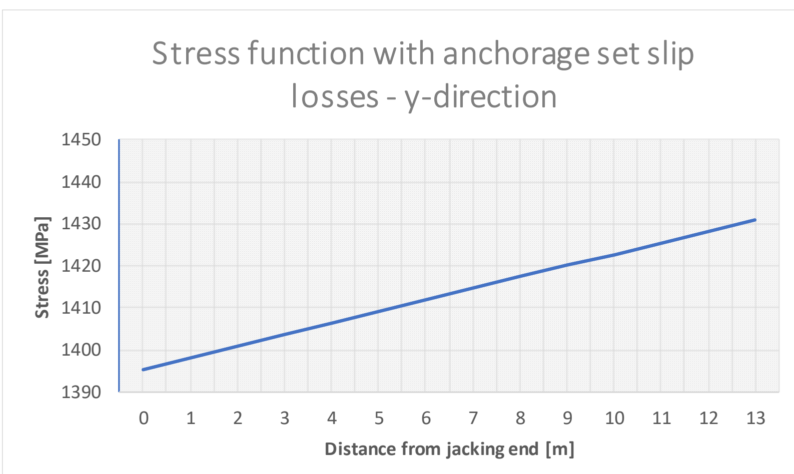
Distance from anchor to where the effect of draw-in does no longer affect the loss

$$\Delta P_{sl.y} := 2 \cdot \beta_y \cdot L_{d.y} = 13.875 \cdot kN$$

Loss of prestressing force due to wedge draw-in at the anchorage

$$\Delta\sigma_{sl.y} := \frac{\Delta P_{sl.y}}{A_p} = 92.501 \cdot MPa$$

Loss of stress due to wedge draw-in at the anchorage



$$P_{avg.y} := 1414.3MPa \cdot A_p = 212.145 \cdot kN$$

Average stress in tendon
(for further calculations)

x-direction:

$$\beta_x := \frac{\Delta P_{\mu.x}}{L_x} = 0.246 \cdot \frac{kN}{m}$$

Slope of the friction loss line

$$L_{d.x} := \sqrt{\frac{(\Delta slip \cdot E_p \cdot A_p)}{\beta_x}} = 21.856\,m$$

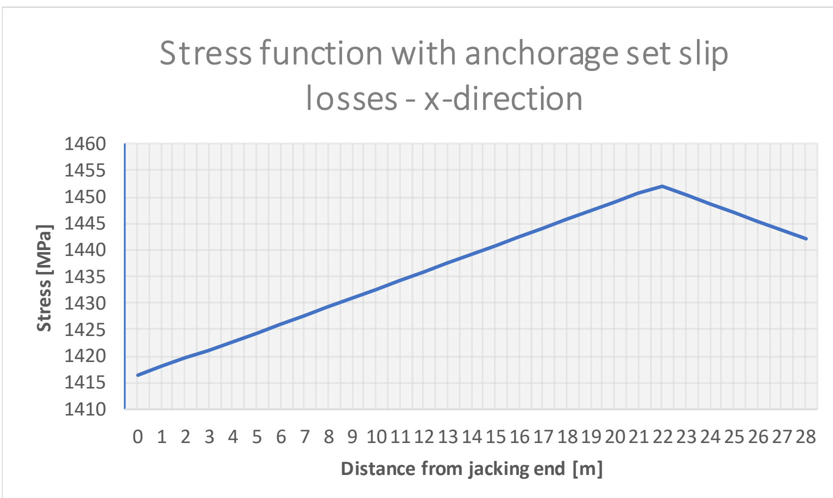
Distance from anchor to where the effect of draw-in does no longer affect the loss

$$\Delta P_{sl.x} := 2 \cdot \beta_x \cdot L_{d.x} = 10.762 \cdot kN$$

Loss of prestressing force due to wedge draw-in at the anchorage

$$\Delta\sigma_{sl.x} := \frac{\Delta P_{sl.x}}{A_p} = 71.743 \cdot MPa$$

Loss of stress due to wedge draw-in at the anchorage



$$P_{avg.x} := 1438.3MPa \cdot A_p = 215.745 \cdot kN$$

Average stress in tendon (for further calculations)

Due to elastic shortening of concrete, EC2-1-1 clause 5.10.5.1

$E_{cm} := 34000MPa$ Mean elastic modulus of concrete

$j := 0.5$ Coefficient

$h_{slab} := 200mm$ Slab thickness

$A_c := h_{slab} \cdot 1m = 2 \times 10^5 \cdot mm^2$ Area of 1m strip

$I_c := \frac{1}{12} \cdot 1m \cdot (h_{slab})^3 = 6.667 \times 10^8 \cdot mm^4$ Moment of Inertia for 1m strip

$z_{cp} := 45mm$ Eccentricity of tendon, maximum is used

y-direction:

$N_y := 34$ Number of tendons in y-direction

$N_{y.1m} := 1.227$ Number of tendons in a 1m strip y-direction

$$\Delta\sigma_{c.y} := \frac{N_y P_{avg.y}}{h_{slab} \cdot L_x} + \frac{N_{y.1m} P_{avg.y} \cdot z_{cp}^2}{I_c} = 2.107 \cdot MPa$$

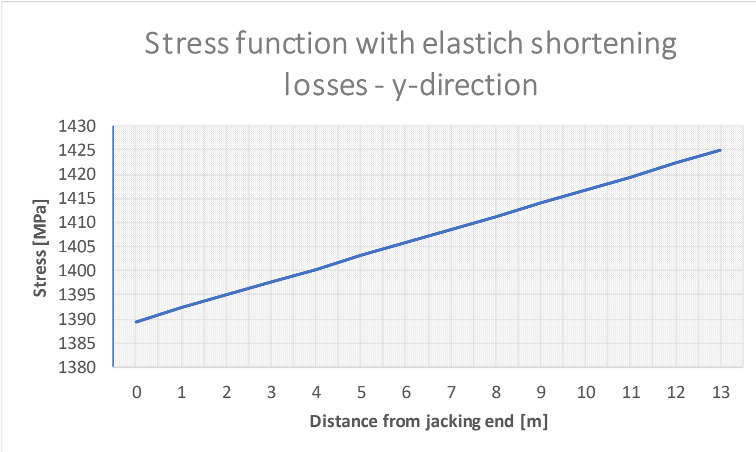
Stress at tendon at maximum eccentricity.
(calculation is simplified by basing on gross cross section)

$$\Delta P_{el.y} := A_p \cdot E_p \cdot \left(\frac{j \cdot \Delta\sigma_{c.y}}{E_{cm}} \right) = 0.911 \cdot kN$$

Calculated loss of force due to the instantaneous deformation of concrete

$$\Delta\sigma_{el.y} := \frac{\Delta P_{el.y}}{A_p} = 6.073 \cdot MPa$$

Calculated loss of stress due to the instantaneous deformation of concrete



$$P_{m0.y} := P_{avg.y} - \Delta P_{el.y} = 211.234 \cdot kN$$

Average prestressing force with initial losses included

x-direction:

$N_x := 24$

Number of tendons in x-direction

$N_{x.1m} := 12$

Number of tendons in a 1m strip x-direction

$$\Delta\sigma_{c.x} := \frac{N_x \cdot P_{avg.x}}{h_{slab} \cdot L_y} + \frac{N_{x.1m} P_{avg.x} \cdot {z_{cp}}^2}{I_c} = 9.952 \cdot MPa$$

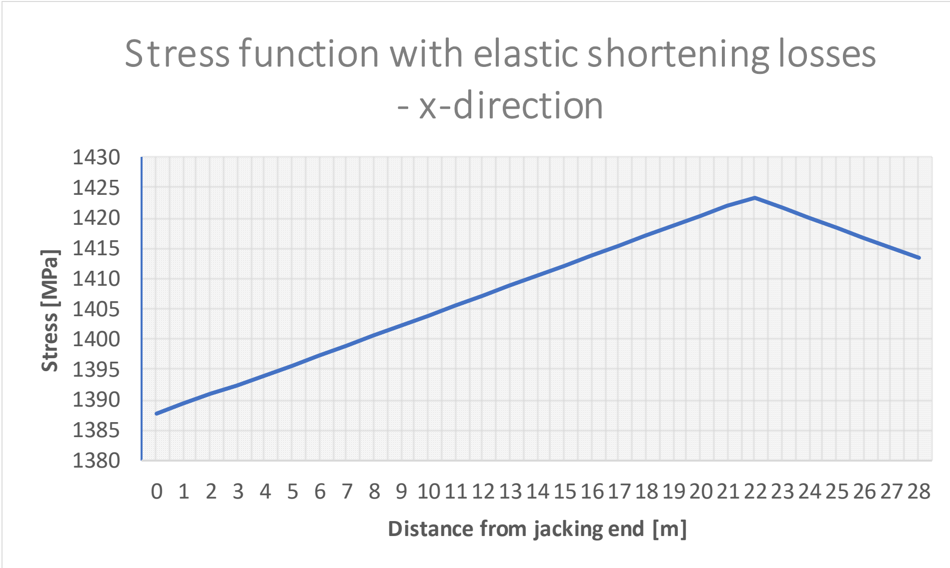
Stress at tendon at maximum eccentricity.
(calculation is simplified by basing on gross cross section)

$$\Delta P_{el.x} := A_p \cdot E_p \cdot \left(\frac{j \cdot \Delta\sigma_{c.x}}{E_{cm}} \right) = 4.303 \cdot kN$$

Calculated loss of force due to the instantaneous deformation of concrete

$$\Delta\sigma_{el.x} := \frac{\Delta P_{el.x}}{A_p} = 28.684 \cdot MPa$$

Calculated loss of stress due to the instantaneous deformation of concrete



$P_{m0.x} := P_{avg.x} - \Delta P_{el.x} = 211.442 \cdot kN$

Average prestressing force with initial losses included

Due to the time dependent losses (creep, shrinkage, relaxation), EC2-1-1 clause 5.10.6

$\varphi := 2.25$	Creep coefficient
$\varepsilon_{cs} := 0.00049$	Shrinkage strain
$f_{p0.1k} := 1640MPa$	Nominal yield strength of tendon
$k_7 := 0.75$	Coefficient, EC2-1-1 clause NA.5.10.3(2)
$k_8 := 0.85$	Coefficient, EC2-1-1 clause NA.5.10.3(2)
$\sigma_{pi} := \min\left(k_7 \cdot f_{pk}, k_8 \cdot f_{p0.1k}\right) = 1.394 \times 10^3 \cdot MPa$	Initial prestress, EC2-1-1 clause 5.10.3(2)
$\rho_{1000} := 2.5$	Losses of relaxation in percentage 1000 hours after stressing with a mean temperature of 20 degrees. Relaxation class 2 - low relaxation
$t := 500000$	Time after stressing, EC2-1-1 clause 3.3.2(8)
$\mu_r := \dfrac{\sigma_{pi}}{f_{pk}} = 0.749$	EC2-1-1 clause 3.3.2(7)
$\Delta\sigma_{pr} := 0.66 \cdot \rho_{1000} \cdot e^{(9.1 \cdot \mu_r)} \cdot \left(\dfrac{t}{1000}\right)^{\left[0.75 \cdot (1-\mu_r)\right]} \cdot 10^{-5} \cdot \sigma_{pi} = 67.737 \cdot MPa$	Absolute value of relaxation loss i the prestressing EC2-1-1 clause 3.3.2(7)
$G_k := 5 \dfrac{kN}{m}$	Selfweight of reinforced concrete
$Q_k := 3 \dfrac{kN}{m}$	Charactheristic live load
$\psi_2 := 0.3$	Load factor for permanent part of live load
$q := G_k + \psi_2 \cdot Q_k = 5.9 \cdot \dfrac{kN}{m}$	Load combination for dead load and live load

y-direction:

$$span_y := 6m$$ Span in y-direction

$$M_q := 0.125 \cdot q \cdot span_y^{\,2} = 26.55 \cdot kN \cdot m$$ Moment over support y-direction

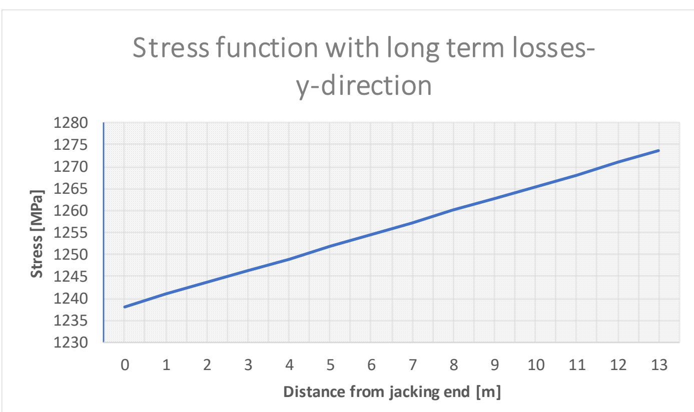
$$\sigma_{c.QP.y} := \frac{N_y(P_{m0.y})}{h_{slab} \cdot L_x} + \frac{N_{y.1m}(P_{m0.y}) \cdot z_{cp}^{\,2}}{I_c} - M_q \cdot \frac{z_{cp}}{I_c} = 0.306 \cdot MPa$$ Stress in the concrete at tendon caused by permanent loads

$$\Delta\sigma_{p.c.s.r.y} := \frac{\varepsilon_{cs} \cdot E_p + 0.8 \cdot \Delta\sigma_{pr} + \frac{E_p}{E_{cm}} \cdot \varphi \cdot \sigma_{c.QP.y}}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\,2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 151.252 \cdot MPa$$ Total long term losses

$$\frac{\varepsilon_{cs} \cdot E_p}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\,2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 94.207 \cdot MPa$$ Losses due to shrinkage

$$\frac{0.8 \cdot \Delta\sigma_{pr}}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\,2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 53.155 \cdot MPa$$ Losses due to relaxation

$$\frac{\frac{E_p}{E_{cm}} \cdot \varphi \cdot \sigma_{c.QP.y}}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\,2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 3.89 \cdot MPa$$ Losses due to creep



$$P_{mt.y} := P_{m0.y} - \left(\Delta\sigma_{p.c.s.r.y} \cdot A_p\right) = 188.546 \cdot kN$$ Prestressing force with all losses included

x-direction:

$span_x := 9m$ Span in x-direction

$M_q := 0.1 \cdot q \cdot span_x^{\ 2} = 47.79 \cdot kN \cdot m$ Moment over support x-direction

$$\sigma_{c.QP.x} := \frac{N_x(P_{m0.x})}{h_{slab} \cdot L_y} + \frac{N_{x.1m}(P_{m0.x}) \cdot z_{cp}^{\ 2}}{I_c} - M_q \cdot \frac{z_{cp}}{I_c} = 6.527 \cdot MPa$$

Stress in the concrete at tendon caused by permanent loads

$$\Delta\sigma_{p.c.s.r.x} := \frac{\varepsilon_{cs} \cdot E_p + 0.8 \cdot \Delta\sigma_{pr} + \frac{E_p}{E_{cm}} \cdot \varphi \cdot \sigma_{c.QP.x}}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\ 2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 230.411 \cdot MPa$$

Total long term losses

$$\frac{\varepsilon_{cs} \cdot E_p}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\ 2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 94.207 \cdot MPa$$

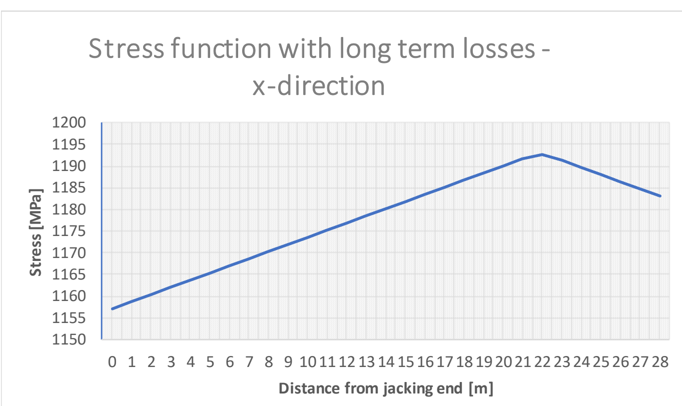
Losses due to shrinkage

$$\frac{0.8 \cdot \Delta\sigma_{pr}}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\ 2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 53.155 \cdot MPa$$

Losses due to relaxation

$$\frac{\frac{E_p}{E_{cm}} \cdot \varphi \cdot \sigma_{c.QP.x}}{1 + \frac{E_p}{E_{cm}} \cdot \frac{A_p}{A_c} \cdot \left(1 + \frac{A_c}{I_c} \cdot z_{cp}^{\ 2}\right) \cdot (1 + 0.8 \cdot \varphi)} = 83.049 \cdot MPa$$

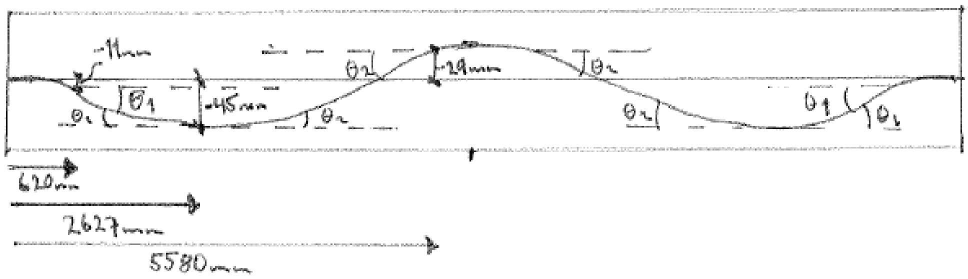
Losses due to creep



$P_{mt.x} := P_{m0.x} - \left(\Delta\sigma_{p.c.s.r.x} \cdot A_p\right) = 176.881 \cdot kN$ Prestressing force with all losses included

Appendix H – Angular displacement for friction loss calculations

Calculation of angular displacement in y-direction:



$$\boxed{\theta_y = 4\cdot\theta_1 + 4\cdot\theta_2}$$

$$y = ax^2 + bx + c$$

$x = 620$, $y = -11$ $\rightarrow$ $-11 = a\cdot 620^2 + b\cdot 620 + c$

$$\boxed{c = -11 - a\cdot 620^2 - b\cdot 620}$$

$x = 2627$, $y = -45$ $\rightarrow$ $-45 = a\cdot 2627^2 + b\cdot 2627 + c$

$\rightarrow$ $-45 = a\cdot 2627^2 + b\cdot 2627 + (-11 - a\cdot 620^2 - b\cdot 620)$

$\rightarrow$ $-45 = a\cdot 6516729 + b\cdot 2007 - 11$

$\rightarrow$ $\boxed{b = -\frac{34}{2007} - 3247\cdot a}$

$x = 5580$, $y = 29$ $\rightarrow$ $29 = a\cdot 5580^2 + b\cdot 5580 + c$

$\rightarrow$ $29 = a\cdot 5580^2 + b\cdot 5580 + (-11 - a\cdot 620^2 - b\cdot 620)$

$\rightarrow$ $29 = 30752000a + 4960b - 11$

$\rightarrow$ $40 = 30752000a + 4960\left(-\frac{34}{2007} - 3247a\right)$

$\rightarrow$ $40 = 14646880a - \frac{168640}{2007}$

$\rightarrow$ $a = \dfrac{40 + \frac{168640}{2007}}{14646880}$

$\rightarrow$ $\underline{a = 8{,}4677\cdot 10^{-6}}$

$$b = -\frac{34}{2007} - 3247 \cdot 8{,}4677 \cdot 10^{-6} = \underline{-4{,}4435 \cdot 10^{-2}}$$

$$c = -11 - 8{,}4677 \cdot 10^{-6} \cdot 620^{2} + 4{,}4435 \cdot 10^{-2} \cdot 620 = \underline{13{,}295}$$

$$\boxed{y = 8{,}4677 \cdot 10^{-6} x^{2} - 4{,}4435 \cdot 10^{-2} x + 13{,}295}$$

$$\boxed{\frac{dy}{dx} = 1{,}6935 \cdot 10^{-5} \cdot x - 4{,}4435 \cdot 10^{-2}}$$

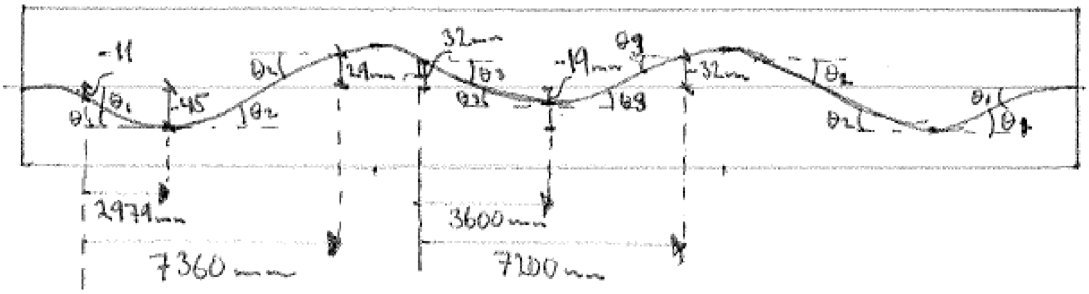
$$\theta_1 = \left.\frac{dy}{dx}\right|_{x=620} = 1{,}6935 \cdot 10^{-5} \cdot 620 - 4{,}4435 \cdot 10^{-2} = \underline{-3{,}3935 \cdot 10^{-2}}$$

$$\theta_2 = \left.\frac{dy}{dx}\right|_{x=5580} = 1{,}6935 \cdot 10^{-5} \cdot 5580 - 4{,}4435 \cdot 10^{-2} = \underline{5{,}0062 \cdot 10^{-2}}$$

$$\theta_y = 4 \cdot |\theta_1| + 4 \cdot |\theta_2| = 4 \cdot 3{,}3935 \cdot 10^{-2} + 4 \cdot 5{,}0062 \cdot 10^{-2} = \underline{\underline{0{,}33599}}$$

$\theta_y = 0{,}33599$

Calculation of angular displacement in x-direction:



$$\boxed{\theta_x = 4\cdot\theta_1 + 4\cdot\theta_2 + 4\cdot\theta_3}$$

$$y = ax^2 + bx + c$$

Parabola 1

$x = 0,\ y = -11 \rightarrow -11 = a0^2 + b\cdot 0 + c$

$\rightarrow \underline{c = -11}$

$x = 2979,\ y = -45 \rightarrow -45 = a\cdot 2979^2 + b\cdot 2979 + c$

$\rightarrow -45 = a\cdot 2979^2 + b\cdot 2979 - 11$

$\rightarrow \underline{b = -2979a - 34/2979}$

$x = 7360,\ y = 29 \rightarrow 29 = a\cdot 7360^2 + b\cdot 7360 + c$

$\rightarrow 29 = a\cdot 7360^2 + 7360\left(-2979a - \frac{34}{2979}\right) - 11$

$\rightarrow 29 = 32244160a - \frac{250240}{2979} - 11$

$\rightarrow \underline{a = 3{,}8457\cdot 10^{-6}}$

$b = -2979\left(3{,}8457\cdot 10^{-6}\right) - \frac{34}{2979} = \underline{-2{,}2870\cdot 10^{-2}}$

$$\boxed{y = 3{,}8457\cdot 10^{-6}\cdot x^2 - 2{,}2870\cdot 10^{-2}\cdot x - 11}$$

$$\boxed{\frac{dy}{dx} = 7{,}6914\cdot 10^{-6}\cdot x - 2{,}2870\cdot 10^{-2}}$$

$\theta_1 = \left.\frac{dy}{dx}\right|_{x=0} = \underline{-2{,}2870\cdot 10^{-2}}$

$\theta_2 = \left.\frac{dy}{dx}\right|_{x=7360} = 7{,}6914\cdot 10^{-6}\cdot 7360 - 2{,}2870\cdot 10^{-2} = \underline{3{,}3739\cdot 10^{-2}}$

Parabola 2

$x = 0,\quad y = 32 \rightarrow 32 = a \cdot 0^2 + b \cdot 0 + c$

$\rightarrow \underline{c = 32}$

$x = 3600,\ y = -19 \rightarrow -19 = a \cdot 3600^2 + b \cdot 3600 + c$

$\rightarrow -19 = a \cdot 3600^2 + b \cdot 3600 + 32$

$\rightarrow \underline{b = -a \cdot 3600 - 51/3600}$

$x = 7200,\ y = 32 \rightarrow 32 = a \cdot 7200^2 + b \cdot 7200 + c$

$\rightarrow 32 = a \cdot 7200^2 + 7200\left(-a \cdot 3600 - \frac{51}{3600}\right) + 32$

$\rightarrow 32 = 25920000\,a - 102 + 32$

$\rightarrow \underline{a = \frac{17}{4320000}}$

$b = -\frac{17}{4320000} \cdot 3600 - \frac{51}{3600} = \underline{-\frac{17}{600}}$

$$\boxed{y = \frac{17}{4320000}x^2 - \frac{17}{600}x + 32}$$

$$\boxed{\frac{dy}{dx} = \frac{17}{2160000}x - \frac{17}{600}}$$

$\theta_3 = \left.\frac{dy}{dx}\right|_{x=0} = \underline{-\frac{17}{600}}$

$\theta_x = 4 \cdot |\theta_1| + 4 \cdot |\theta_2| + 4 \cdot |\theta_3|$

$= 4 \cdot 2{,}2870 \cdot 10^{-2} + 4 \cdot 3{,}3739 \cdot 10^{-2} + 4 \cdot \frac{17}{600}$

$= \underline{\underline{0{,}33978}}$

$\theta_x = 0{,}33978$

Appendix I - Stress calculations

$span_x := 9m$	Length of span in x-direction
$span_y := 6m$	Length of span in y-direction
$h_{slab} := 200mm$	Slab thickness
$A_{c.x} := span_y \cdot h_{slab} = 1.2 \times 10^6 \cdot mm^2$	Area for full width of interior strip in x-direction
$A_{c.y} := span_x \cdot h_{slab} = 1.8 \times 10^6 \cdot mm^2$	Area for full width of interior strip in y-direction
$I_{c.x} := \frac{1}{12} \cdot span_y \cdot h_{slab}^3 = 4 \times 10^9 \cdot mm^4$	Second moment of area of interior strip in x-direction
$I_{c.y} := \frac{1}{12} \cdot span_x \cdot h_{slab}^3 = 6 \times 10^9 \cdot mm^4$	Second moment of area of interior strip in y-direction
$e := 45mm$	Maximum eccentricity of tendon over column and in field
$P_{m0.x} := 211.4kN$	Prestressing force in x-direction with initial losses included
$P_{mt.x} := 176.9kN$	Prestressing force in x-direction with all losses included
$P_{m0.y} := 211.2kN$	Prestressing force in y-direction with initial losses included
$P_{mt.y} := 188.5kN$	Prestressing force in y-direction with all losses included
$N_{strip.x} := 12$	Number of tendons in strip, x-direction
$N_{strip.y} := 11.33$	Number of tendons in strip, y-direction
$q_{initial} := 5 \frac{kN}{m^2}$	Initial load
$q_{service} := 5 \frac{kN}{m^2} + 0.3 \cdot 3 \frac{kN}{m^2} = 5.9 \cdot \frac{kN}{m^2}$	Load at service (quasi-permanent)

At column:

X-direction:

Initial load combination:

$$M := 0.1 \cdot span_y \cdot q_{initial} \cdot span_x^{\,2} = 243 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{m0.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{m0.x} \cdot N_{strip.x} \cdot (e) \left(\frac{h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.x}} = 1.107 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{m0.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{m0.x} \cdot N_{strip.x} \cdot (e) \left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} = -5.335 \cdot MPa$$

Quasi-permanent load combination:

$$M := 0.1 \cdot span_y \cdot q_{service} \cdot span_x^{\,2} = 286.74 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{mt.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{mt.x} \cdot N_{strip.x} \cdot (e) \left(\frac{h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.x}} = 3.011 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{mt.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{mt.x} \cdot N_{strip.x} \cdot (e) \left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} = -6.549 \cdot MPa$$

Y-direction:

Initial load combination:

$$M := 0.125 \cdot span_x \cdot q_{initial} \cdot span_y^{\,2} = 202.5 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{m0.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{m0.y} \cdot N_{strip.y} \cdot (e)\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} = 0.251 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{m0.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{m0.y} \cdot N_{strip.y} \cdot (e)\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} = -2.91 \cdot MPa$$

Quasi-permanent load combination:

$$M := 0.125 \cdot span_x \cdot q_{service} \cdot span_y^{\,2} = 238.95 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{mt.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{mt.y} \cdot N_{strip.y} \cdot (e)\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} = 1.194 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{mt.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{mt.y} \cdot N_{strip.y} \cdot (e)\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} = -3.567 \cdot MPa$$

At span:

X-direction:

Initial load combination:

$$M := -0.08 \cdot span_y \cdot q_{initial} \cdot span_x^2 = -194.4 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{m0.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{m0.x} \cdot N_{strip.x} \cdot (-e)\left(\frac{h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.x}} = -4.12 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{m0.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{m0.x} \cdot N_{strip.x} \cdot (-e)\left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} = -0.108 \cdot MPa$$

Quasi-permanent load combination:

$$M := -0.08 \cdot span_y \cdot q_{service} \cdot span_x^2 = -229.392 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{mt.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{mt.x} \cdot N_{strip.x} \cdot (-e)\left(\frac{h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.x}} = -5.116 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{mt.x} \cdot N_{strip.x}}{A_{c.x}} + \frac{-P_{mt.x} \cdot N_{strip.x} \cdot (-e)\left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.x}} = 1.578 \cdot MPa$$

Y-direction:

Initial load combination:

$$M := -0.0703 \cdot span_x \cdot q_{initial} \cdot span_y^2 = -113.886 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{m0.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{m0.y} \cdot N_{strip.y} \cdot (-e)\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} = -1.433 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{m0.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{m0.y} \cdot N_{strip.y} \cdot (-e)\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} = -1.226 \cdot MPa$$

Quasi-permanent load combination:

$$M := -0.0703 \cdot span_x \cdot q_{service} \cdot span_y^2 = -134.385 \cdot kN \cdot m$$

$$\sigma_{c.top} := \frac{-P_{mt.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{mt.y} \cdot N_{strip.y} \cdot (-e)\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{h_{slab}}{2}\right)}{I_{c.y}} = -1.824 \cdot MPa$$

$$\sigma_{c.btm} := \frac{-P_{mt.y} \cdot N_{strip.y}}{A_{c.y}} + \frac{-P_{mt.y} \cdot N_{strip.y} \cdot (-e)\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} + M \cdot \frac{\left(\frac{-h_{slab}}{2}\right)}{I_{c.y}} = -0.549 \cdot MPa$$

Appendix J - Bending moment calculations

Design bending moments:

$span_x := 9m$	Length of span in x-direction
$span_y := 6m$	Length of span in y-direction
$h_{slab} := 200mm$	Slab thickness
$\gamma_g := 1.2$	Load factor for dead load
$\gamma_q := 1.5$	Load factor for live load
$\gamma_p := 1$	Load factor for prestressing. NOTE: According to EC2-1-1 this should be 0,9 or 1,1. 1,0 is used for this comparement.
$g_k := 25\frac{kN}{m^3}\cdot h_{slab} = 5\cdot\frac{kN}{m^2}$	Characteristic dead load
$q_k := 3\frac{kN}{m^2}$	Characteristic live load
$N_{x.strip} := 12$	Number of tendons in interior strip x-direction
$N_{y.strip} := \frac{34}{3} = 11.333$	Number of tendons in interior strip y-direction
$P_{mt.x} := 176.88kN$	Prestressing force per tendon in x-direction with all losses included
$P_{mt.y} := 188.55kN$	Prestressing force per tendon in y-direction with all losses included
$h := 68mm$	Drape of idealized tendon parabola
$e := 45mm$	Maximum eccentricity

Hand calculations are based on simple beam theory and idealized parabolic model.

X-direction:

$$q_{p.x} := \frac{N_{x.strip} \cdot P_{mt.x} \cdot 8 \cdot h}{span_x^2} = 14.255 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons

$$M_{p.column.x} := 0.1 \cdot q_{p.x} \cdot span_x^2 = 115.467 \cdot kN \cdot m$$

Prestressing moment at column

$$M_{p.span.x} := -0.08 \cdot q_{p.x} \cdot span_x^2 = -92.374 \cdot kN \cdot m$$

Prestressing moment in span

$$M_{0.column.x} := N_{x.strip} \cdot P_{mt.x} \cdot e = 95.515 \cdot kN \cdot m$$

Primary moment at column

$$M_{0.span.x} := N_{x.strip} \cdot P_{mt.x} \cdot -e = -95.515 \cdot kN \cdot m$$

Primary moment in span

$$M_{Ek.h.column.x} := M_{p.column.x} - M_{0.column.x} = 19.952 \cdot kN \cdot m$$

Characteristic hyperstatic moment at column

$$M_{Ek.h.span.x} := M_{p.span.x} - M_{0.span.x} = 3.141 \cdot kN \cdot m$$

Characteristic hyperstatic moment in span

$$M_{Ek.g.column.x} := -0.1 \cdot g_k \cdot span_y \cdot span_x^2 = -243 \cdot kN \cdot m$$

Characteristic moment at column due to dead load

$$M_{Ek.g.span.x} := 0.08 \cdot g_k \cdot span_y \cdot span_x^2 = 194.4 \cdot kN \cdot m$$

Characteristic moment in span due to dead load

$$M_{Ek.q.column.x} := -0.117 \cdot q_k \cdot span_y \cdot span_x^2 = -170.586 \cdot kN \cdot m$$

Characteristic moment at column due to live load

$$M_{Ek.q.span.x} := 0.101 \cdot q_k \cdot span_y \cdot span_x^2 = 147.258 \cdot kN \cdot m$$

Characteristic moment in span due to live load

Design moments:

$$M_{Ed.column.x} := \gamma_g \cdot M_{Ek.g.column.x} + \gamma_q \cdot M_{Ek.q.column.x} + \gamma_p \cdot M_{Ek.h.column.x} = -527.527 \cdot kN \cdot m$$

$$M_{Ed.span.x} := \gamma_g \cdot M_{Ek.g.span.x} + \gamma_q \cdot M_{Ek.q.span.x} + \gamma_p \cdot M_{Ek.h.span.x} = 457.308 \cdot kN \cdot m$$

Y-direction:

$$q_{p.y} := \frac{N_{y.strip} \cdot P_{mt.y} \cdot 8 \cdot h}{span_y^2} = 32.291 \cdot \frac{kN}{m}$$ Equivalent upward force from tendons

$$M_{p.column.y} := 0.125 \cdot q_{p.y} \cdot span_y^2 = 145.309 \cdot kN \cdot m$$ Prestressing moment at column

$$M_{p.span.y} := -0.0703 \cdot q_{p.y} \cdot span_y^2 = -81.722 \cdot kN \cdot m$$ Prestressing moment in span

$$M_{0.column.y} := N_{y.strip} \cdot P_{mt.y} \cdot e = 96.16 \cdot kN \cdot m$$ Primary moment at column

$$M_{0.span.y} := N_{y.strip} \cdot P_{mt.y} \cdot -e = -96.16 \cdot kN \cdot m$$ Primary moment in span

$$M_{Ek.h.column.y} := M_{p.column.y} - M_{0.column.y} = 49.149 \cdot kN \cdot m$$ Characteristic hyperstatic moment at column

$$M_{Ek.h.span.y} := M_{p.span.y} - M_{0.span.y} = 14.439 \cdot kN \cdot m$$ Characteristic hyperstatic moment in span

$$M_{Ek.g.column.y} := -0.125 \cdot g_k \cdot span_x \cdot span_y^2 = -202.5 \cdot kN \cdot m$$ Characteristic moment at column due to dead load

$$M_{Ek.g.span.y} := 0.0703 \cdot g_k \cdot span_x \cdot span_y^2 = 113.886 \cdot kN \cdot m$$ Characteristic moment in span due to dead load

$$M_{Ek.q.column.y} := -0.125 \cdot q_k \cdot span_x \cdot span_y^2 = -121.5 \cdot kN \cdot m$$ Characteristic moment at column due to live load

$$M_{Ek.q.span.y} := 0.0957 \cdot q_k \cdot span_x \cdot span_y^2 = 93.02 \cdot kN \cdot m$$ Characteristic moment in span due to live load

Design moments:

$$M_{Ed.column.y} := \gamma_g \cdot M_{Ek.g.column.y} + \gamma_q \cdot M_{Ek.q.column.y} + \gamma_p \cdot M_{Ek.h.column.y} = -376.101 \cdot kN \cdot m$$

$$M_{Ed.span.y} := \gamma_g \cdot M_{Ek.g.span.y} + \gamma_q \cdot M_{Ek.q.span.y} + \gamma_p \cdot M_{Ek.h.span.y} = 290.632 \cdot kN \cdot m$$

Bending moment capacity:

$\Delta\sigma_{p.ULS} := 100MPa$ Increase of stress in ULS

$A_p := 150mm^2$ Cross-sectional area of one tendon

$f_{yd} := 434.8MPa$ Design strength of the reinforcement

$d_p := \frac{h_{slab}}{2} + e = 145 \cdot mm$ Effective slab thickness due to tendons

$f_{cd} := \frac{0.85 \cdot 35MPa}{1.5} = 19.833 \cdot MPa$ Design compression strength of concrete

$A_{10} := \pi \cdot (5mm)^2 = 78.54 \cdot mm^2$ Cross-sectional area of rebar ø10

X-direction:

$b_x := \frac{span_y}{2} = 3\ m$ — Effective width of section. Half span due to banded tendons.

$A_{s.top.x} := 22 \cdot A_{10} = 1.728 \times 10^3 \cdot mm^2$ — Reinforcement in top at column

$A_{s.btm.x} := \frac{b_x}{270mm} \cdot A_{10} = 872.665 \cdot mm^2$ — Reinforcement in bottom in span

$d_{d.x} := 170mm$ — Effective slab thickness due to reinforcement

$S_{p.x} := N_{x.strip} \cdot \left(P_{mt.x} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 2.303 \times 10^3 \cdot kN$ — Forces in tendons

$S_{d.top.x} := f_{yd} \cdot A_{s.top.x} = 751.28 \cdot kN$ — Forces in reinforcement, top

$S_{d.btm.x} := f_{yd} \cdot A_{s.btm.x} = 379.435 \cdot kN$ — Forces in reinforcement, bottom

$d_{eff.column.x} := \frac{d_p \cdot S_{p.x} + d_{d.x} \cdot S_{d.top.x}}{S_{p.x} + S_{d.top.x}} = 151.15 \cdot mm$ — Effective slab thickness due to tendons and reinforcement combined, at column

$d_{eff.span.x} := \frac{d_p \cdot S_{p.x} + d_{d.x} \cdot S_{d.btm.x}}{S_{p.x} + S_{d.btm.x}} = 148.537 \cdot mm$ — Effective slab thickness due to tendons and reinforcement combined, in span

$\alpha_{column.x} := \frac{S_{p.x} + S_{d.top.x}}{0.8 \cdot f_{cd} \cdot b_x \cdot d_{eff.column.x}} = 0.424$ — Factor, at column

$\alpha_{span.x} := \frac{S_{p.x} + S_{d.btm.x}}{0.8 \cdot f_{cd} \cdot b_x \cdot d_{eff.span.x}} = 0.379$ — Factor, in span

Moment capacities:

$$M_{Rd.column.x} := -0.8 \cdot \alpha_{column.x} \cdot \left(1 - 0.4 \cdot \alpha_{column.x}\right) \cdot b_x \cdot d_{eff.column.x}^{\ 2} \cdot f_{cd} = -383.22 \cdot kN \cdot m$$

$$M_{Rd.span.x} := 0.8 \cdot \alpha_{span.x} \cdot \left(1 - 0.4 \cdot \alpha_{span.x}\right) \cdot b_x \cdot d_{eff.span.x}^{\ 2} \cdot f_{cd} = 337.929 \cdot kN \cdot m$$

Y-direction:

$b_y := span_x = 9\,m$

Effective width of section. Half span due to banded tendons.

$A_{s.top.y} := 31 \cdot A_{10} = 2.435 \times 10^3 \cdot mm^2$

Reinforcement in top at column

$A_{s.btm.y} := \frac{b_y}{270mm} \cdot A_{10} = 2.618 \times 10^3 \cdot mm^2$

Reinforcement in bottom in span

$d_{d.y} := 160mm$

Effective slab thickness due to reinforcement

$S_{p.y} := N_{y.strip} \cdot \left(P_{mt.y} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 2.307 \times 10^3 \cdot kN$

Forces in tendons

$S_{d.top.y} := f_{yd} \cdot A_{s.top.y} = 1.059 \times 10^3 \cdot kN$

Forces in reinforcement, top

$S_{d.btm.y} := f_{yd} \cdot A_{s.btm.y} = 1.138 \times 10^3 \cdot kN$

Forces in reinforcement, bottom

$d_{eff.column.y} := \frac{d_p \cdot S_{p.y} + d_{d.y} \cdot S_{d.top.y}}{S_{p.y} + S_{d.top.y}} = 149.718 \cdot mm$

Effective slab thickness due to tendons and reinforcement combined, at column

$d_{eff.span.y} := \frac{d_p \cdot S_{p.y} + d_{d.y} \cdot S_{d.btm.y}}{S_{p.y} + S_{d.btm.y}} = 149.956 \cdot mm$

Effective slab thickness due to tendons and reinforcement combined, in span

$\alpha_{column.y} := \frac{S_{p.y} + S_{d.top.y}}{0.8 \cdot f_{cd} \cdot b_y \cdot d_{eff.column.y}} = 0.157$

Factor, at column

$\alpha_{span.y} := \frac{S_{p.y} + S_{d.btm.y}}{0.8 \cdot f_{cd} \cdot b_y \cdot d_{eff.span.y}} = 0.161$

Factor, in span

Moment capacities:

$M_{Rd.column.y} := -0.8 \cdot \alpha_{column.y} \cdot \left(1 - 0.4 \cdot \alpha_{column.y}\right) \cdot b_y \cdot d_{eff.column.y}^{\ 2} \cdot f_{cd} = -472.153 \cdot kN \cdot m$

$M_{Rd.span.y} := 0.8 \cdot \alpha_{span.y} \cdot \left(1 - 0.4 \cdot \alpha_{span.y}\right) \cdot b_y \cdot d_{eff.span.y}^{\ 2} \cdot f_{cd} = 483.381 \cdot kN \cdot m$

Appendix K - Shear calculations

$d_{d.x} := 170mm$	Effective slab thickness due to reinforcement in x-direction
$d_{d.y} := 160mm$	Effective slab thickness due to reinforcement in y-direction
$D := 400mm$	Diameter of column
$\gamma_c := 1.5$	Partial factor of concrete
$f_{ck} := 35MPa$	Characteristic compression strength of concrete
$f_{cd} := 19.8MPa$	Design compression strength of concrete
$span_x := 9m$	Length of span in x-direction
$span_y := 6m$	Length of span in y-direction
$h_{slab} := 200mm$	Slab thickness
$f_{yk} := 500MPa$	Characteristic yield strength of reinforcement
$f_{ywd} := 434.8MPa$	Design yield strength of the shear reinforcement

Design shear forces are chosen equal to the reaction forces in the columns calculated in ADAPT:

$V_{Ed.inner} := 749.2kN$

$V_{Ed.edge} := 281.5kN$

$V_{Ed.corner} := 113.0kN$

$d_{eff} := \frac{d_{d.y} + d_{d.x}}{2} = 165 \cdot mm$ (EC2-1-1: 6.4.2(1))

$2 \cdot d_{eff} = 330 \cdot mm$ Distance from column edge to basic control perimeter

Control perimeters:

$u_{1.inner} := \pi\left(D + 4 \cdot d_{eff}\right) = 3.33 \times 10^{3} \cdot mm$ Basic control perimeter, inner column

$u_{0.inner} := \pi \cdot D = 1.257 \times 10^{3} \cdot mm$ Column edge perimeter, inner column

$u_{1.edge} := \frac{u_{1.inner}}{2} = 1.665 \times 10^{3} \cdot mm$ Basic control perimeter, edge column

$u_{0.edge} := \frac{u_{0.inner}}{2} = 628.319 \cdot mm$ Column edge perimeter, edge column

$u_{1.corner} := \frac{u_{1.inner}}{4} = 832.522 \cdot mm$ Basic control perimeter, corner column

$u_{0.corner} := \frac{u_{0.inner}}{4} = 314.159 \cdot mm$ Column edge perimeter, corner column

$\beta := 1$ Assumed due to hinged releases / no moments in columns

Shear stresses in control perimeter: (EC2-1-1: 6.4.3(3))

$$v_{Ed.u1.inner} := \beta \cdot \frac{V_{Ed.inner}}{u_{1.inner} \cdot d_{eff}} = 1.364 \cdot \frac{N}{mm^2}$$ Inner column

$$v_{Ed.u1.edge} := \beta \cdot \frac{V_{Ed.edge}}{u_{1.edge} \cdot d_{eff}} = 1.025 \cdot \frac{N}{mm^2}$$ Edge column

$$v_{Ed.u1.corner} := \beta \cdot \frac{V_{Ed.corner}}{u_{1.corner} \cdot d_{eff}} = 0.823 \cdot \frac{N}{mm^2}$$ Corner column

Shear stress at column edges, u0: (EC2-1-1: 6.4.3(3))

$$v_{Ed.u0.inner} := \beta \cdot \frac{V_{Ed.inner}}{u_{0.inner} \cdot d_{eff}} = 3.613 \cdot \frac{N}{mm^2}$$

$$v_{Ed.u0.edge} := \beta \cdot \frac{V_{Ed.edge}}{u_{0.edge} \cdot d_{eff}} = 2.715 \cdot \frac{N}{mm^2}$$

$$v_{Ed.u0.corner} := \beta \cdot \frac{V_{Ed.corner}}{u_{0.corner} \cdot d_{eff}} = 2.18 \cdot \frac{N}{mm^2}$$

Punching shear resistance without shear reinforcement:

$$k_2 := 0.18$$ (EC2-1-1: NA.6.4.4(1))

$$C_{Rd.c} := \frac{k_2}{\gamma_c} = 0.12$$ (EC2-1-1: NA.6.4.4(1))

$$k_1 := 0.1$$ (EC2-1-1: NA.6.4.4(1))

$$k := \min\left(1 + \sqrt{\frac{200mm}{d_{eff}}}, 2\right) = 2$$ (EC2-1-1: 6.4.4(1))

$$v_{min} := 0.035 \cdot k^{\frac{3}{2}} \cdot f_{ck}^{\frac{1}{2}} \cdot MPa^{\frac{1}{2}} = 0.586 \cdot MPa$$ (EC2-1-1: NA.6.4.4(1))

Reinforcement ratios, based on minimum reinforcement: (EC2-1-1: 6.2.2(1))

(EC2-1-1: 6.4.4(1))

$$\rho_{ly.inner} := \min\left[\frac{\pi\cdot(5mm)^2\cdot 1}{75mm\cdot d_{d.y}}, 0.02\right] = 6.545 \times 10^{-3}$$

$$\rho_{lx.inner} := \min\left[\frac{\pi\cdot(5mm)^2\cdot 1}{70mm\cdot d_{d.x}}, 0.02\right] = 6.6 \times 10^{-3}$$

$$\rho_{l.inner} := \min\left(\sqrt{\rho_{ly.inner}\cdot\rho_{lx.inner}}, 0.02\right) = 6.572 \times 10^{-3}$$

$$\rho_{ly.edge} := \min\left[\frac{\pi\cdot(5mm)^2\cdot 1}{75mm\cdot d_{d.y}}, 0.02\right] = 6.545 \times 10^{-3}$$

$$\rho_{lx.edge} := 0 = 0$$

$$\rho_{l.edge} := \min\left(\sqrt{\rho_{ly.edge}\cdot\rho_{lx.edge}}, 0.02\right) = 0$$

$$\rho_{ly.corner} := 0 = 0$$

$$\rho_{lx.corner} := 0 = 0$$

$$\rho_{l.corner} := \min\left(\sqrt{\rho_{ly.corner}\cdot\rho_{lx.corner}}, 0.02\right) = 0$$

$\sigma_{cx} := 1.786MPa$ Average stress in structure in x-direction

$\sigma_{cy} := 1.124MPa$ Average stress in structure in y-direction

$$\sigma_{cp} := \frac{\sigma_{cy} + \sigma_{cx}}{2} = 1.455 \cdot MPa$$ (EC2-1-1: 6.4.4(1))

Inner column:

$$v_{Rd.c.inner} := \max\left[C_{Rd.c} \cdot k \cdot \left(100 \cdot \rho_{l.inner} \cdot f_{ck}\right)^{\frac{1}{3}} \cdot MPa^{\frac{2}{3}} + k_1 \cdot \sigma_{cp}, v_{min} + k_1 \cdot \sigma_{cp}\right] = 0.828 \cdot MPa$$

$$v_{Rd.c0.inner} := \max\left[C_{Rd.c} \cdot k \cdot \left(100 \cdot \rho_{l.inner} \cdot f_{ck}\right)^{\frac{1}{3}} \cdot MPa^{\frac{2}{3}}, v_{min}\right] = 0.683 \cdot MPa$$ (Without axial stress)

$$v_{Rd.c.edge} := \max\left[C_{Rd.c} \cdot k \cdot \left(100 \cdot \rho_{l.edge} \cdot f_{ck}\right)^{\frac{1}{3}} \cdot MPa^{\frac{2}{3}} + k_1 \cdot \sigma_{cp}, v_{min} + k_1 \cdot \sigma_{cp}\right] = 0.731 \cdot MPa$$

$$v_{Rd.c0.edge} := \max\left[C_{Rd.c} \cdot k \cdot \left(100 \cdot \rho_{l.edge} \cdot f_{ck}\right)^{\frac{1}{3}} \cdot MPa^{\frac{2}{3}}, v_{min}\right] = 0.586 \cdot MPa$$ (Without axial stress)

$$v_{Rd.c.corner} := \max\left[\begin{matrix} C_{Rd.c} \cdot k \cdot \left(100 \cdot \rho_{l.corner} \cdot f_{ck}\right)^{\frac{1}{3}} \cdot MPa^{\frac{2}{3}} \ldots, v_{min} \ldots \\ + k_1 \cdot \sigma_{cp} \qquad + k_1 \cdot \sigma_{cp} \end{matrix}\right] = 0.731 \cdot MPa$$

$$v_{Rd.c0.corner} := \max\left[C_{Rd.c} \cdot k \cdot \left(100 \cdot \rho_{l.corner} \cdot f_{ck}\right)^{\frac{1}{3}} \cdot MPa^{\frac{2}{3}}, v_{min}\right] = 0.586 \cdot MPa$$ (Without axial stress)

Maximum punching shear resistance:

$$\nu := 0.6\left(1 - \frac{f_{ck}}{250MPa}\right) = 0.516$$ (EC2-1-1: NA.6.2.2(6))

$$v_{Rd.max} := 0.4 \cdot \nu \cdot f_{cd} = 4.087 \cdot MPa$$ (EC2-1-1: NA.6.4.5(3))

With limitations:

$$v_{Rd.max.inner} := \min\left(0.4 \cdot \nu \cdot f_{cd}, 1.6 \cdot v_{Rd.c0.inner} \cdot \frac{u_{1.inner}}{\beta \cdot u_{0.inner}}\right) = 2.894 \cdot MPa$$

$$v_{Rd.max.edge} := \min\left(0.4 \cdot \nu \cdot f_{cd}, 1.6 \cdot v_{Rd.c0.edge} \cdot \frac{u_{1.edge}}{\beta \cdot u_{0.edge}}\right) = 2.483 \cdot MPa$$

$$v_{Rd.max.corner} := \min\left(0.4 \cdot \nu \cdot f_{cd}, 1.6 \cdot v_{Rd.c0.corner} \cdot \frac{u_{1.corner}}{\beta \cdot u_{0.corner}}\right) = 2.483 \cdot MPa$$

With limitations:

	Inner column		Edge column		Corner column	
	At control perimeter	At column edge	At control perimeter	At column edge	At control perimeter	At column edge
vEd	1.364	3.613	1.025	2.715	0.823	2.18
VRd	0.828	2.894	0.731	2.483	0.731	2.483
Utilization	1.65	1.25	1.40	1.09	1.13	0.88

Without limitations:

	Inner column	Edge column	Corner column
vEd	3.613	2.715	2.18
VRd	4.087	4.087	4.087
Utilization	0.88	0.66	0.53

Conclusion:

- Shear reinforcement is needed at all columns
- Shear reinforcement for inner and edge columns must be calculated without concrete contribution

Shear reinforcement: (only inner column is calculated)

Control perimeter where shear reinforcement is not necessary:

$$u_{out.inner} := \beta \cdot \frac{V_{Ed.inner}}{v_{Rd.c.inner} \cdot d_{eff}} = 5.483 \times 10^{3} \cdot mm$$ (EC2-1-1: 6.4.5(4))

$$s_{r.max} := 0.75 \cdot d_{eff} = 123.75 \cdot mm$$ Maximum radial spacing (EC2-1-1: 9.4.3(1))

--> choose: $s_r := 120mm$

$$d_{u1.inner} := \frac{\left(\frac{u_{1.inner}}{\pi} - D\right)}{2} = 330 \cdot mm$$ Distance from column edge to control perimeter

$$d_{u.out.inner} := \frac{\left(\frac{u_{out.inner}}{\pi} - D\right)}{2} = 672.712 \cdot mm$$ Distance from column edge to perimeter where shear reinforcement is not necessary

$$d_{intersection.1.min} := 0.3 \cdot d_{eff} = 49.5 \cdot mm$$ Minimum distance from column edge to first perimeter

$$d_{intersection.1.max} := 0.5 \cdot d_{eff} = 82.5 \cdot mm$$ Maximum distance from column edge to first perimeter

$$d_{perimeter.last.min} := d_{u.out.inner} - 1 \cdot d_{eff} = 507.712 \cdot mm$$ Minimum distance from column edge to last perimeter (EC2-1-1: NA.6.4.5(4))

Perimeter 1: $P_1 := 70mm$

Perimeter 2: $P_2 := 70mm + s_r = 190 \cdot mm$

Perimeter 3: $P_3 := 70mm + 2 \cdot s_r = 310 \cdot mm$

Perimeter 4: $P_4 := 70mm + 3 \cdot s_r = 430 \cdot mm$

Perimeter 5: $P_5 := 70mm + 4 \cdot s_r = 550 \cdot mm$ (> $d_{perimeter.last}$)

$s_{t.max} := 1.5 \cdot d_{eff} = 247.5 \cdot mm$ Maximum tangential spacing inside control perimeter u_1 (EC2-1-1: 9.4.3(1))

$s_{t.max.out} := 2 \cdot d_{eff} = 330 \cdot mm$ Maximum tangential spacing outside control perimeter u_1 (EC2-1-1: 9.4.3(1))

--> choose $s_t := 240mm$

$\alpha := \frac{\pi}{2}$ Angle between shear reinforcement and plane of the plate, 90 degrees

$$f_{ywd.ef} := \min\left(250MPa + 0.25 \cdot d_{eff} \cdot \frac{MPa}{mm}, f_{ywd}\right) = 291.25 \cdot MPa$$

Effective design strength of the punching shear reinforcement (EC2-1-1: 6.4.5(1))

$$A_{sw.req} := \frac{\left(v_{Ed.u1.inner}\right) \cdot s_r \cdot u_{1.inner}}{1.5 \cdot f_{ywd.ef} \cdot \sin(\alpha)} = 1.247 \times 10^3 \cdot mm^2$$

Required shear reinforcement per perimeter

$$A_{sw.min} := \frac{\left(0.08 \cdot \sqrt{f_{ck}} \cdot s_r \cdot s_t\right) \cdot N^{\frac{1}{2}}}{1.5 \cdot f_{yk} \cdot mm} = 18.174 \cdot mm^2$$

Minimum cross section per link leg (EC2-1-1: 9.4.3(2))

--> chooses ø10 $A_{10} := \pi \cdot (5mm)^2 = 78.54 \cdot mm^2$

$$n_{req} := \frac{A_{sw.req}}{A_{10}} = 15.88$$

--> $n := 16$ 16 legs per perimeter

Using stud rails:

$$st_5 := \frac{\pi \cdot \left(2 \cdot P_5 + D\right)}{n} = 294.524 \cdot mm$$

Tangential spacing in outer perimeter

< $s_{t.max.out}$ --> OK!

$$st_3 := \frac{\pi \cdot \left(2 \cdot P_3 + D\right)}{n} = 200.277 \cdot mm$$

Tangential spacing in outer perimeter inside of control perimeter

< $s_{t.max}$ --> OK!

Summary:
- 16 stud rails with 5 studs ø10 in each over inner columns

Appendix L - Stresses in tendon layout analysis with two decimals

		ADAPT				FEM-Design			
		X1 (span)		X2 (column)		X1 (span)		X2 (column)	
		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
6X6	A	-2,95	0,51	0,88	-3,18	-3,62	0,25	6,66	-9,07
	B	-3,09	0,30	1,01	-3,11	-3,22	-0,37	4,74	-7,05
	C	-3,07	0,52	1,23	-3,27	-3,36	0,92	6,50	-8,74
	D	-3,07	0,45	1,12	-3,17	-3,21	0,38	5,78	-8,05
	E	-2,98	0,57	1,08	-3,23	-3,43	0,75	6,64	-8,95
	F	-	-	-	-	-3,58	3,58	11,56	-11,56
9X6	A	-4,52	1,52	1,95	-5,09	-5,01	1,59	8,51	-11,66
	B	-4,84	1,13	2,15	-4,82	-4,85	0,68	5,45	-8,25
	C	-4,95	0,99	2,15	-4,84	-4,99	0,96	6,60	-9,58
	D	-4,89	1,06	2,12	-4,80	-4,89	0,71	5,84	-8,75
	E	-4,72	1,25	2,07	-4,92	-4,94	1,14	6,90	-9,91
	F	-	-	-	-	-5,49	5,49	14,56	-14,56
11X6	A	-5,05	1,92	2,40	-5,58	-4,55	1,26	6,26	-9,47
	B	-5,35	1,44	2,78	-5,33	-4,60	0,39	2,81	-5,45
	C	-5,41	1,42	2,86	-5,38	-4,77	0,44	3,83	-6,61
	D	-5,36	1,46	2,82	-5,34	-4,62	0,41	3,19	-5,92
	E	-5,22	1,63	2,67	-5,48	-4,61	0,74	4,60	-7,58
	F	-	-	-	-	-5,48	5,48	12,60	-12,60

Values in MPa, positive values are tensile stresses, x-direction, quasi-permanent load combination

		ADAPT				FEM-Design			
		Y1 (span)		Y2 (column)		Y1 (span)		Y2 (column)	
		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
6X6	A	-2,79	0,29	1,30	-3,56	-2,83	0,27	6,57	-9,00
	B	-2,83	0,11	1,04	-3,43	-2,84	-0,74	4,82	-7,41
	C	-2,78	0,20	0,94	-3,43	-3,24	-0,26	6,80	-9,45
	D	-2,80	0,16	0,98	-3,44	-3,19	-0,34	5,91	-8,55
	E	-2,77	0,25	1,12	-3,50	-3,18	0,15	6,71	-9,29
	F	-	-	-	-	-3,10	3,10	11,95	-11,95
9X6	A	-2,00	-0,05	0,24	-2,32	-2,27	0,33	7,09	-9,27
	B	-1,99	-0,19	0,11	-2,20	-2,08	-2,04	3,62	-6,38
	C	-1,97	-0,14	0,16	-2,17	-2,38	-1,23	5,79	-8,46
	D	-1,98	-0,17	0,14	-2,20	-2,39	-1,70	4,43	-7,15
	E	-1,99	-0,17	0,11	-2,23	-2,47	-0,95	5,62	-8,23
	F	-	-	-	-	-3,17	3,17	12,98	-12,98
11X6	A	-1,60	-0,24	-0,12	-1,72	-1,47	-0,46	4,46	-6,37
	B	-1,57	-0,36	-0,22	-1,61	-1,25	-2,96	0,03	-2,91
	C	-1,58	-0,32	-0,17	-1,63	-1,98	0,17	2,06	-4,91
	D	-1,57	-0,35	-0,21	-1,61	-1,56	-2,65	0,81	-3,69
	E	-1,57	-0,29	-0,17	-1,65	-1,62	-1,62	2,67	-5,14
	F	-	-	-	-	-2,33	2,33	10,15	-10,15

Values in MPa, positive values are tensile stresses, y-direction, quasi-permanent load combination

Appendix M - Bending moment capacities due to a column strip/middle strip approach

$span_x := 9m$	Length of span in x-direction
$span_y := 6m$	Length of span in y-direction
$h_{slab} := 220mm$	Slab thickness
$\gamma_g := 1.2$	Load factor for dead load
$\gamma_q := 1.5$	Load factor for live load
$\gamma_p := 1$	Load factor for prestressing. NOTE: According to EC2-1-1 this should be 0,9 or 1,1. 1,0 is used for this comparement.
$g_k := 25\frac{kN}{m^3}\cdot h_{slab} = 5.5\cdot\frac{kN}{m^2}$	Characteristic dead load
$q_k := 3\frac{kN}{m^2}$	Characteristic live load
$P_{mt} := 178.56kN$	Prestressing force per tendon with all losses included
$h := 77mm$	Drape of idealized tendon parabola
$e_{bottom} := 55mm$	Maximum eccentricity bottom
$e_{top} := 43mm$	Maximum eccentricity top

Hand calculations are based on simple beam theory, distribution of 70/30% between column and middle strip for negative moments, distribution of 60/40% between column and middle strip for positive moments, and idealized parabolic model.

X-direction:

$M_{Ek.g.column.x.cstrip} := -0.1 \cdot g_k \cdot span_y \cdot span_x^2 \cdot 0.7 = -187.11 \cdot kN \cdot m$

Characteristic moment at column due to dead load, column strip

$M_{Ek.g.span.x.cstrip} := 0.08 \cdot g_k \cdot span_y \cdot span_x^2 \cdot 0.6 = 128.3 \cdot kN \cdot m$

Characteristic moment in span due to dead load, column strip

$M_{Ek.g.column.x.mstrip} := -0.1 \cdot g_k \cdot span_y \cdot span_x^2 \cdot 0.3 = -80.19 \cdot kN \cdot m$

Characteristic moment at column due to dead load, middle strip

$M_{Ek.g.span.x.mstrip} := 0.08 \cdot g_k \cdot span_y \cdot span_x^2 \cdot 0.4 = 85.54 \cdot kN \cdot m$

Characteristic moment in span due to dead load, middle strip

$M_{Ek.q.column.x.cstrip} := -0.117 \cdot q_k \cdot span_y \cdot span_x^2 \cdot 0.7 = -119.41 \cdot kN \cdot m$

Characteristic moment at column due to live load, column strip

$M_{Ek.q.span.x.cstrip} := 0.101 \cdot q_k \cdot span_y \cdot span_x^2 \cdot 0.6 = 88.35 \cdot kN \cdot m$

Characteristic moment in span due to live load, column strip

$M_{Ek.q.column.x.mstrip} := -0.117 \cdot q_k \cdot span_y \cdot span_x^2 \cdot 0.3 = -51.18 \cdot kN \cdot m$

Characteristic moment at column due to live load, middle strip

$M_{Ek.q.span.x.mstrip} := 0.101 \cdot q_k \cdot span_y \cdot span_x^2 \cdot 0.4 = 58.9 \cdot kN \cdot m$

Characteristic moment in span due to live load, middle strip

Y-direction:

$$M_{Ek.g.column.y.cstrip} := -0.125 \cdot g_k \cdot span_x \cdot span_y^2 \cdot 0.7 = -155.93 \cdot kN \cdot m$$

Characteristic moment at column due to dead load, column strip

$$M_{Ek.g.span.y.cstrip} := 0.0703 \cdot g_k \cdot span_x \cdot span_y^2 \cdot 0.6 = 75.16 \cdot kN \cdot m$$

Characteristic moment in span due to dead load, column strip

$$M_{Ek.g.column.y.mstrip} := -0.125 \cdot g_k \cdot span_x \cdot span_y^2 \cdot 0.3 = -66.83 \cdot kN \cdot m$$

Characteristic moment at column due to dead load, middle strip

$$M_{Ek.g.span.y.mstrip} := 0.0703 \cdot g_k \cdot span_x \cdot span_y^2 \cdot 0.4 = 50.11 \cdot kN \cdot m$$

Characteristic moment in span due to dead load, middle strip

$$M_{Ek.q.column.y.cstrip} := -0.125 \cdot q_k \cdot span_x \cdot span_y^2 \cdot 0.7 = -85.05 \cdot kN \cdot m$$

Characteristic moment at column due to live load, column strip

$$M_{Ek.q.span.y.cstrip} := 0.0957 \cdot q_k \cdot span_x \cdot span_y^2 \cdot 0.6 = 55.81 \cdot kN \cdot m$$

Characteristic moment in span due to live load, column strip

$$M_{Ek.q.column.y.mstrip} := -0.125 \cdot q_k \cdot span_x \cdot span_y^2 \cdot 0.3 = -36.45 \cdot kN \cdot m$$

Characteristic moment at column due to live load, middle strip

$$M_{Ek.q.span.y.mstrip} := 0.0957 \cdot q_k \cdot span_x \cdot span_y^2 \cdot 0.4 = 37.21 \cdot kN \cdot m$$

Characteristic moment in span due to live load, middle strip

$\Delta\sigma_{p.ULS} := 100MPa$ — Increase of stress in ULS

$A_p := 150mm^2$ — Cross-sectional area of one tendon

$f_{yd} := 434.8MPa$ — Design strength of the reinforcement

$d_{p.column} := \frac{h_{slab}}{2} + e_{top} = 153 \cdot mm$ — Effective slab thickness due to tendons at column

$d_{p.span} := \frac{h_{slab}}{2} + e_{bottom} = 165 \cdot mm$ — Effective slab thickness due to tendons in span

$f_{cd} := \frac{0.85 \cdot 45MPa}{1.5} = 25.5 \cdot MPa$ — Design compression strength of concrete

$A_{10} := \pi \cdot (5mm)^2 = 78.54 \cdot mm^2$ — Cross-sectional area of rebar ø10

$A_{16} := \pi \cdot (8mm)^2 = 201.06 \cdot mm^2$ — Cross-sectional area of rebar ø16

$A_{s.top.x.cstrip} := 8 \cdot A_{16} = 1.61 \times 10^3 \cdot mm^2$ — Reinforcement in top at column in x-direction, column strip

$A_{s.top.y.cstrip} := 9 \cdot A_{16} = 1.81 \times 10^3 \cdot mm^2$ — Reinforcement in top at column in y-direction, column strip

$A_{s.top.x.mstrip} := 4 \cdot A_{16} = 804.25 \cdot mm^2$ — Reinforcement in top at column in x-direction, middle strip

$A_{s.top.y.mstrip} := 7 \cdot A_{16} = 1.41 \times 10^3 \cdot mm^2$ — Reinforcement in top at column in y-direction, middle strip

$A_{s.btm} := \frac{1}{200mm} \cdot A_{10} = 392.7 \frac{1}{m} \cdot mm^2$ — Reinforcement in bottom in span, per meter

$d_{d.column.x} := 187mm$ Effective slab thickness due to reinforcement, column, x-direction

$d_{d.span.x} := 190mm$ Effective slab thickness due to reinforcement, span, x-direction

$d_{d.column.y} := 171mm$ Effective slab thickness due to reinforcement, column, y-direction

$d_{d.span.y} := 180mm$ Effective slab thickness due to reinforcement, span, y-direction

$S_{d.top.x.cstrip} := f_{yd} \cdot A_{s.top.x.cstrip} = 699.37 \cdot kN$ Forces in reinforcement, top, x-direction, column strip

$S_{d.btm.x.cstrip} := f_{yd} \cdot A_{s.btm} \cdot 3m = 512.24 \cdot kN$ Forces in reinforcement, bottom, x-direction, column strip

$S_{d.top.x.mstrip} := f_{yd} \cdot A_{s.top.x.mstrip} = 349.69 \cdot kN$ Forces in reinforcement, top, x-direction, middle strip

$S_{d.btm.x.mstrip} := f_{yd} \cdot A_{s.btm} \cdot 3m = 512.24 \cdot kN$ Forces in reinforcement, bottom, x-direction, middle strip

$S_{d.top.y.cstrip} := f_{yd} \cdot A_{s.top.y.cstrip} = 786.8 \cdot kN$ Forces in reinforcement, top, y-direction, column strip

$S_{d.btm.y.cstrip} := f_{yd} \cdot A_{s.btm} \cdot 3m = 512.24 \cdot kN$ Forces in reinforcement, bottom, y-direction, column strip

$S_{d.top.y.mstrip} := f_{yd} \cdot A_{s.top.y.mstrip} = 611.95 \cdot kN$ Forces in reinforcement, top, y-direction, middle strip

$S_{d.btm.y.mstrip} := f_{yd} \cdot A_{s.btm} \cdot 6m = 1.02 \times 10^3 \cdot kN$ Forces in reinforcement, bottom, y-direction, middle strip

Tendon layout A

$N_{x.cstrip} := 12$ Number of tendons in interior strip x-direction, column strip

$N_{x.mstrip} := 0$ Number of tendons in interior strip x-direction, middle strip

$N_{y.cstrip} := 4$ Number of tendons in interior strip y-direction, column strip

$N_{y.mstrip} := 8$ Number of tendons in interior strip y-direction, middle strip

$$q_{p.x.cstrip} := \frac{N_{x.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 16.3 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, column strip

$$q_{p.x.mstrip} := \frac{N_{x.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, middle strip

$$q_{p.y.cstrip} := \frac{N_{y.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 12.22 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, column strip

$$q_{p.y.mstrip} := \frac{N_{y.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 24.44 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, middle strip

$M_{p.column.x.cstrip} := 0.1 \cdot q_{p.x.cstrip} \cdot span_x^2 = 131.99 \cdot kN \cdot m$ Prestressing moment at column, x-direction, column strip

$M_{p.span.x.cstrip} := -0.08 \cdot q_{p.x.cstrip} \cdot span_x^2 = -105.59 \cdot kN \cdot m$ Prestressing moment in span, x-direction, column strip

$M_{p.column.x.mstrip} := 0.1 \cdot q_{p.x.mstrip} \cdot span_x^2 = 0 \cdot kN \cdot m$ Prestressing moment at column, x-direction, middle strip

$M_{p.span.x.mstrip} := -0.08 \cdot q_{p.x.mstrip} \cdot span_x^2 = 0 \cdot kN \cdot m$ Prestressing moment in span, x-direction, middle strip

$M_{p.column.y.cstrip} := 0.125 \cdot q_{p.y.cstrip} \cdot span_y^2 = 55 \cdot kN \cdot m$ Prestressing moment at column, y-direction, column strip

$M_{p.span.y.cstrip} := -0.0703 \cdot q_{p.y.cstrip} \cdot span_y^2 = -30.93 \cdot kN \cdot m$ Prestressing moment in span, y-direction, column strip

$M_{p.column.y.mstrip} := 0.125 \cdot q_{p.y.mstrip} \cdot span_y^2 = 109.99 \cdot kN \cdot m$ Prestressing moment at column, y-direction, middle strip

$M_{p.span.y.mstrip} := -0.0703 \cdot q_{p.y.mstrip} \cdot span_y^2 = -61.86 \cdot kN \cdot m$ Prestressing moment in span, y-direction, middle strip

$M_{0.column.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot e_{top} = 92.14 \cdot kN \cdot m$ Primary moment at column, x-direction, column strip

$M_{0.span.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -117.85 \cdot kN \cdot m$ Primary moment in span, x-direction, column strip

$M_{0.column.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, x-direction, middle strip

$M_{0.span.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, x-direction, middle strip

$M_{0.column.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot e_{top} = 30.71 \cdot kN \cdot m$ Primary moment at column, y-direction, column strip

$M_{0.span.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -39.28 \cdot kN \cdot m$ Primary moment in span, y-direction, column strip

$M_{0.column.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot e_{top} = 61.42 \cdot kN \cdot m$ Primary moment at column, y-direction, middle strip

$M_{0.span.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot -e_{bottom} = -78.57 \cdot kN \cdot m$ Primary moment in span, y-direction, middle strip

Characteristic hyperstatic moments:

$M_{Ek.h.column.x.cstrip} := M_{p.column.x.cstrip} - M_{0.column.x.cstrip} = 39.85 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.span.x.cstrip} := M_{p.span.x.cstrip} - M_{0.span.x.cstrip} = 12.26 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.column.x.mstrip} := M_{p.column.x.mstrip} - M_{0.column.x.mstrip} = 0 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.span.x.mstrip} := M_{p.span.x.mstrip} - M_{0.span.x.mstrip} = 0 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.column.y.cstrip} := M_{p.column.y.cstrip} - M_{0.column.y.cstrip} = 24.28 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.span.y.cstrip} := M_{p.span.y.cstrip} - M_{0.span.y.cstrip} = 8.35 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.column.y.mstrip} := M_{p.column.y.mstrip} - M_{0.column.y.mstrip} = 48.57 \cdot kN \cdot m$ y-direction, middle strip

$M_{Ek.h.span.y.mstrip} := M_{p.span.y.mstrip} - M_{0.span.y.mstrip} = 16.71 \cdot kN \cdot m$ y-direction, middle strip

Design moments:

$$M_{Ed.column.x.cstrip} := \gamma_g \cdot M_{Ek.g.column.x.cstrip} + \gamma_q \cdot M_{Ek.q.column.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.cstrip} = -363.79 \cdot kN \cdot m$$

$$M_{Ed.span.x.cstrip} := \gamma_g \cdot M_{Ek.g.span.x.cstrip} + \gamma_q \cdot M_{Ek.q.span.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.cstrip} = 298.75 \cdot kN \cdot m$$

$$M_{Ed.column.x.mstrip} := \gamma_g \cdot M_{Ek.g.column.x.mstrip} + \gamma_q \cdot M_{Ek.q.column.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.mstrip} = -172.99 \cdot kN \cdot m$$

$$M_{Ed.span.x.mstrip} := \gamma_g \cdot M_{Ek.g.span.x.mstrip} + \gamma_q \cdot M_{Ek.q.span.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.mstrip} = 191 \cdot kN \cdot m$$

$$M_{Ed.column.y.cstrip} := \gamma_g \cdot M_{Ek.g.column.y.cstrip} + \gamma_q \cdot M_{Ek.q.column.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.cstrip} = -290.4 \cdot kN \cdot m$$

$$M_{Ed.span.y.cstrip} := \gamma_g \cdot M_{Ek.g.span.y.cstrip} + \gamma_q \cdot M_{Ek.q.span.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.cstrip} = 182.27 \cdot kN \cdot m$$

$$M_{Ed.column.y.mstrip} := \gamma_g \cdot M_{Ek.g.column.y.mstrip} + \gamma_q \cdot M_{Ek.q.column.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.mstrip} = -86.3 \cdot kN \cdot m$$

$$M_{Ed.span.y.mstrip} := \gamma_g \cdot M_{Ek.g.span.y.mstrip} + \gamma_q \cdot M_{Ek.q.span.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.mstrip} = 132.65 \cdot kN \cdot m$$

$S_{p.x.cstrip} := N_{x.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 2.32 \times 10^3 \cdot kN$

Forces in tendons, x-direction, column strip

$S_{p.x.mstrip} := N_{x.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$

Forces in tendons, x-direction, middle strip

$S_{p.y.cstrip} := N_{y.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 774.24 \cdot kN$

Forces in tendons, y-direction, column strip

$S_{p.y.mstrip} := N_{y.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 1.55 \times 10^3 \cdot kN$

Forces in tendons, y-direction, middle strip

Effective slab thicknesses:

$$d_{eff.column.x.cstrip} := \frac{d_{p.column} \cdot S_{p.x.cstrip} + d_{d.column.x} \cdot S_{d.top.x.cstrip}}{S_{p.x.cstrip} + S_{d.top.x.cstrip}} = 160.87 \cdot mm$$

$$d_{eff.span.x.cstrip} := \frac{d_{p.span} \cdot S_{p.x.cstrip} + d_{d.span.x} \cdot S_{d.btm.x.cstrip}}{S_{p.x.cstrip} + S_{d.btm.x.cstrip}} = 169.52 \cdot mm$$

$$d_{eff.column.x.mstrip} := \frac{d_{p.column} \cdot S_{p.x.mstrip} + d_{d.column.x} \cdot S_{d.top.x.mstrip}}{S_{p.x.mstrip} + S_{d.top.x.mstrip}} = 187 \cdot mm$$

$$d_{eff.span.x.mstrip} := \frac{d_{p.span} \cdot S_{p.x.mstrip} + d_{d.span.x} \cdot S_{d.btm.x.mstrip}}{S_{p.x.mstrip} + S_{d.btm.x.mstrip}} = 190 \cdot mm$$

$$d_{eff.column.y.cstrip} := \frac{d_{p.column} \cdot S_{p.y.cstrip} + d_{d.column.y} \cdot S_{d.top.y.cstrip}}{S_{p.y.cstrip} + S_{d.top.y.cstrip}} = 162.07 \cdot mm$$

$$d_{eff.span.y.cstrip} := \frac{d_{p.span} \cdot S_{p.y.cstrip} + d_{d.span.y} \cdot S_{d.btm.y.cstrip}}{S_{p.y.cstrip} + S_{d.btm.y.cstrip}} = 170.97 \cdot mm$$

$$d_{eff.column.y.mstrip} := \frac{d_{p.column} \cdot S_{p.y.mstrip} + d_{d.column.y} \cdot S_{d.top.y.mstrip}}{S_{p.y.mstrip} + S_{d.top.y.mstrip}} = 158.1 \cdot mm$$

$$d_{eff.span.y.mstrip} := \frac{d_{p.span} \cdot S_{p.y.mstrip} + d_{d.span.y} \cdot S_{d.btm.y.mstrip}}{S_{p.y.mstrip} + S_{d.btm.y.mstrip}} = 170.97 \cdot mm$$

α-factors:

$$\alpha_{column.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.top.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.cstrip}} = 0.31$$

$$\alpha_{span.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.btm.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.cstrip}} = 0.27$$

$$\alpha_{column.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.top.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.mstrip}} = 0.03$$

$$\alpha_{span.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.btm.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.mstrip}} = 0.04$$

$$\alpha_{column.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.top.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.y.cstrip}} = 0.16$$

$$\alpha_{span.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.btm.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.y.cstrip}} = 0.12$$

$$\alpha_{column.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.top.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.column.y.mstrip}} = 0.11$$

$$\alpha_{span.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.btm.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.span.y.mstrip}} = 0.12$$

Moment capacities:

$$M_{Rd.column.x.cstrip} := -0.8\cdot\alpha_{column.x.cstrip}\cdot\left(1-0.4\cdot\alpha_{column.x.cstrip}\right)\cdot 3m\cdot d_{eff.column.x.cstrip}^{\;2}\cdot f_{cd} = -426.47\cdot$$

$$M_{Rd.span.x.cstrip} := 0.8\cdot\alpha_{span.x.cstrip}\cdot\left(1-0.4\cdot\alpha_{span.x.cstrip}\right)\cdot 3m\cdot d_{eff.span.x.cstrip}^{\;2}\cdot f_{cd} = 428.04\cdot kN\cdot m$$

$$M_{Rd.column.x.mstrip} := -0.8\cdot\alpha_{column.x.mstrip}\cdot\left(1-0.4\cdot\alpha_{column.x.mstrip}\right)\cdot 3m\cdot d_{eff.column.x.mstrip}^{\;2}\cdot f_{cd} = -64.5$$

$$M_{Rd.span.x.mstrip} := 0.8\cdot\alpha_{span.x.mstrip}\cdot\left(1-0.4\cdot\alpha_{span.x.mstrip}\right)\cdot 3m\cdot d_{eff.span.x.mstrip}^{\;2}\cdot f_{cd} = 95.61\cdot kN\cdot m$$

$$M_{Rd.column.y.cstrip} := -0.8\cdot\alpha_{column.y.cstrip}\cdot\left(1-0.4\cdot\alpha_{column.y.cstrip}\right)\cdot 3m\cdot d_{eff.column.y.cstrip}^{\;2}\cdot f_{cd} = -237.07\cdot$$

$$M_{Rd.span.y.cstrip} := 0.8\cdot\alpha_{span.y.cstrip}\cdot\left(1-0.4\cdot\alpha_{span.y.cstrip}\right)\cdot 3m\cdot d_{eff.span.y.cstrip}^{\;2}\cdot f_{cd} = 209.14\cdot kN\cdot m$$

$$M_{Rd.column.y.mstrip} := -0.8\cdot\alpha_{column.y.mstrip}\cdot\left(1-0.4\cdot\alpha_{column.y.mstrip}\right)\cdot 6m\cdot d_{eff.column.y.mstrip}^{\;2}\cdot f_{cd} = -326.3$$

$$M_{Rd.span.y.mstrip} := 0.8\cdot\alpha_{span.y.mstrip}\cdot\left(1-0.4\cdot\alpha_{span.y.mstrip}\right)\cdot 6m\cdot d_{eff.span.y.mstrip}^{\;2}\cdot f_{cd} = 418.27\cdot kN\cdot m$$

	X-direction				Y-direction			
	Column strip		Middle strip		Column strip		Middle strip	
	At column	At span	At column	At span	At column	At span	At column	At span
MEd	-363.8	298.8	-173	191	-290.4	182.3	-86.3	132.7
MRd	-426.5	428	-64.6	95.6	-237.1	209.1	-326.3	418.3
Utilization	85 %	70 %	268 %	200 %	122 %	87 %	26 %	32 %

Tendon layout B

$N_{x.cstrip} := 12$ Number of tendons in interior strip x-direction, column strip

$N_{x.mstrip} := 0$ Number of tendons in interior strip x-direction, middle strip

$N_{y.cstrip} := 12$ Number of tendons in interior strip y-direction, column strip

$N_{y.mstrip} := 0$ Number of tendons in interior strip y-direction, middle strip

$$q_{p.x.cstrip} := \frac{N_{x.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 16.3 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, column strip

$$q_{p.x.mstrip} := \frac{N_{x.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, middle strip

$$q_{p.y.cstrip} := \frac{N_{y.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 36.66 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, column strip

$$q_{p.y.mstrip} := \frac{N_{y.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, middle strip

$M_{p.column.x.cstrip} := 0.1 \cdot q_{p.x.cstrip} \cdot span_x^2 = 131.99 \cdot kN \cdot m$ Prestressing moment at column, x-direction, column strip

$M_{p.span.x.cstrip} := -0.08 \cdot q_{p.x.cstrip} \cdot span_x^2 = -105.59 \cdot kN \cdot m$ Prestressing moment in span, x-direction, column strip

$M_{p.column.x.mstrip} := 0.1 \cdot q_{p.x.mstrip} \cdot span_x^2 = 0 \cdot kN \cdot m$ Prestressing moment at column, x-direction, middle strip

$M_{p.span.x.mstrip} := -0.08 \cdot q_{p.x.mstrip} \cdot span_x^2 = 0 \cdot kN \cdot m$ Prestressing moment in span, x-direction, middle strip

$M_{p.column.y.cstrip} := 0.125 \cdot q_{p.y.cstrip} \cdot span_y^2 = 164.99 \cdot kN \cdot m$ Prestressing moment at column, y-direction, column strip

$M_{p.span.y.cstrip} := -0.0703 \cdot q_{p.y.cstrip} \cdot span_y^2 = -92.79 \cdot kN \cdot m$ Prestressing moment in span, y-direction, column strip

$M_{p.column.y.mstrip} := 0.125 \cdot q_{p.y.mstrip} \cdot span_y^2 = 0 \cdot kN \cdot m$ Prestressing moment at column, y-direction, middle strip

$M_{p.span.y.mstrip} := -0.0703 \cdot q_{p.y.mstrip} \cdot span_y^2 = 0 \cdot kN \cdot m$ Prestressing moment in span, y-direction, middle strip

$M_{0.column.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot e_{top} = 92.14 \cdot kN \cdot m$ Primary moment at column, x-direction, column strip

$M_{0.span.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -117.85 \cdot kN \cdot m$ Primary moment in span, x-direction, column strip

$M_{0.column.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, x-direction, middle strip

$M_{0.span.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, x-direction, middle strip

$M_{0.column.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot e_{top} = 92.14 \cdot kN \cdot m$ Primary moment at column, y-direction, column strip

$M_{0.span.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -117.85 \cdot kN \cdot m$ Primary moment in span, y-direction, column strip

$M_{0.column.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, y-direction, middle strip

$M_{0.span.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, y-direction, middle strip

Characteristic hyperstatic moments:

$$M_{Ek.h.column.x.cstrip} := M_{p.column.x.cstrip} - M_{0.column.x.cstrip} = 39.85 \cdot kN \cdot m$$

x-direction, column strip

$$M_{Ek.h.span.x.cstrip} := M_{p.span.x.cstrip} - M_{0.span.x.cstrip} = 12.26 \cdot kN \cdot m$$

x-direction, column strip

$$M_{Ek.h.column.x.mstrip} := M_{p.column.x.mstrip} - M_{0.column.x.mstrip} = 0 \cdot kN \cdot m$$

x-direction, middle strip

$$M_{Ek.h.span.x.mstrip} := M_{p.span.x.mstrip} - M_{0.span.x.mstrip} = 0 \cdot kN \cdot m$$

x-direction, middle strip

$$M_{Ek.h.column.y.cstrip} := M_{p.column.y.cstrip} - M_{0.column.y.cstrip} = 72.85 \cdot kN \cdot m$$

y-direction, column strip

$$M_{Ek.h.span.y.cstrip} := M_{p.span.y.cstrip} - M_{0.span.y.cstrip} = 25.06 \cdot kN \cdot m$$

y-direction, column strip

$$M_{Ek.h.column.y.mstrip} := M_{p.column.y.mstrip} - M_{0.column.y.mstrip} = 0 \cdot kN \cdot m$$

y-direction, middle strip

$$M_{Ek.h.span.y.mstrip} := M_{p.span.y.mstrip} - M_{0.span.y.mstrip} = 0 \cdot kN \cdot m$$

y-direction, middle strip

Design moments:

$$M_{Ed.column.x.cstrip} := \gamma_g \cdot M_{Ek.g.column.x.cstrip} + \gamma_q \cdot M_{Ek.q.column.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.cstrip} = -363.79 \cdot kN \cdot m$$

$$M_{Ed.span.x.cstrip} := \gamma_g \cdot M_{Ek.g.span.x.cstrip} + \gamma_q \cdot M_{Ek.q.span.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.cstrip} = 298.75 \cdot kN \cdot m$$

$$M_{Ed.column.x.mstrip} := \gamma_g \cdot M_{Ek.g.column.x.mstrip} + \gamma_q \cdot M_{Ek.q.column.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.mstrip} = -172.99 \cdot kN \cdot m$$

$$M_{Ed.span.x.mstrip} := \gamma_g \cdot M_{Ek.g.span.x.mstrip} + \gamma_q \cdot M_{Ek.q.span.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.mstrip} = 191 \cdot kN \cdot m$$

$$M_{Ed.column.y.cstrip} := \gamma_g \cdot M_{Ek.g.column.y.cstrip} + \gamma_q \cdot M_{Ek.q.column.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.cstrip} = -241.83 \cdot kN \cdot m$$

$$M_{Ed.span.y.cstrip} := \gamma_g \cdot M_{Ek.g.span.y.cstrip} + \gamma_q \cdot M_{Ek.q.span.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.cstrip} = 198.98 \cdot kN \cdot m$$

$$M_{Ed.column.y.mstrip} := \gamma_g \cdot M_{Ek.g.column.y.mstrip} + \gamma_q \cdot M_{Ek.q.column.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.mstrip} = -134.87 \cdot kN \cdot m$$

$$M_{Ed.span.y.mstrip} := \gamma_g \cdot M_{Ek.g.span.y.mstrip} + \gamma_q \cdot M_{Ek.q.span.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.mstrip} = 115.94 \cdot kN \cdot m$$

$$S_{p.x.cstrip} := N_{x.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 2.32 \times 10^3 \cdot kN$$

Forces in tendons, x-direction, column strip

$$S_{p.x.mstrip} := N_{x.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$$

Forces in tendons, x-direction, middle strip

$$S_{p.y.cstrip} := N_{y.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 2.32 \times 10^3 \cdot kN$$

Forces in tendons, y-direction, column strip

$$S_{p.y.mstrip} := N_{y.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$$

Forces in tendons, y-direction, middle strip

Effective slab thicknesses:

$$d_{eff.column.x.cstrip} := \frac{d_{p.column} \cdot S_{p.x.cstrip} + d_{d.column.x} \cdot S_{d.top.x.cstrip}}{S_{p.x.cstrip} + S_{d.top.x.cstrip}} = 160.87 \cdot mm$$

$$d_{eff.span.x.cstrip} := \frac{d_{p.span} \cdot S_{p.x.cstrip} + d_{d.span.x} \cdot S_{d.btm.x.cstrip}}{S_{p.x.cstrip} + S_{d.btm.x.cstrip}} = 169.52 \cdot mm$$

$$d_{eff.column.x.mstrip} := \frac{d_{p.column} \cdot S_{p.x.mstrip} + d_{d.column.x} \cdot S_{d.top.x.mstrip}}{S_{p.x.mstrip} + S_{d.top.x.mstrip}} = 187 \cdot mm$$

$$d_{eff.span.x.mstrip} := \frac{d_{p.span} \cdot S_{p.x.mstrip} + d_{d.span.x} \cdot S_{d.btm.x.mstrip}}{S_{p.x.mstrip} + S_{d.btm.x.mstrip}} = 190 \cdot mm$$

$$d_{eff.column.y.cstrip} := \frac{d_{p.column} \cdot S_{p.y.cstrip} + d_{d.column.y} \cdot S_{d.top.y.cstrip}}{S_{p.y.cstrip} + S_{d.top.y.cstrip}} = 157.55 \cdot mm$$

$$d_{eff.span.y.cstrip} := \frac{d_{p.span} \cdot S_{p.y.cstrip} + d_{d.span.y} \cdot S_{d.btm.y.cstrip}}{S_{p.y.cstrip} + S_{d.btm.y.cstrip}} = 167.71 \cdot mm$$

$$d_{eff.column.y.mstrip} := \frac{d_{p.column} \cdot S_{p.y.mstrip} + d_{d.column.y} \cdot S_{d.top.y.mstrip}}{S_{p.y.mstrip} + S_{d.top.y.mstrip}} = 171 \cdot mm$$

$$d_{eff.span.y.mstrip} := \frac{d_{p.span} \cdot S_{p.y.mstrip} + d_{d.span.y} \cdot S_{d.btm.y.mstrip}}{S_{p.y.mstrip} + S_{d.btm.y.mstrip}} = 180 \cdot mm$$

α-factors:

$$\alpha_{column.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.top.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.cstrip}} = 0.31$$

$$\alpha_{span.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.btm.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.cstrip}} = 0.27$$

$$\alpha_{column.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.top.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.mstrip}} = 0.03$$

$$\alpha_{span.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.btm.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.mstrip}} = 0.04$$

$$\alpha_{column.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.top.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.y.cstrip}} = 0.32$$

$$\alpha_{span.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.btm.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.y.cstrip}} = 0.28$$

$$\alpha_{column.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.top.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.column.y.mstrip}} = 0.03$$

$$\alpha_{span.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.btm.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.span.y.mstrip}} = 0.05$$

Moment capacities:

$$M_{Rd.column.x.cstrip} := -0.8 \cdot \alpha_{column.x.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.x.cstrip}\right) \cdot 3m \cdot d_{eff.column.x.cstrip}{}^{2} \cdot f_{cd} = -426.47 \cdot$$

$$M_{Rd.span.x.cstrip} := 0.8 \cdot \alpha_{span.x.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.x.cstrip}\right) \cdot 3m \cdot d_{eff.span.x.cstrip}{}^{2} \cdot f_{cd} = 428.04 \cdot kN \cdot m$$

$$M_{Rd.column.x.mstrip} := -0.8 \cdot \alpha_{column.x.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.x.mstrip}\right) \cdot 3m \cdot d_{eff.column.x.mstrip}{}^{2} \cdot f_{cd} = -64.5$$

$$M_{Rd.span.x.mstrip} := 0.8 \cdot \alpha_{span.x.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.x.mstrip}\right) \cdot 3m \cdot d_{eff.span.x.mstrip}{}^{2} \cdot f_{cd} = 95.61 \cdot kN \cdot m$$

$$M_{Rd.column.y.cstrip} := -0.8 \cdot \alpha_{column.y.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.y.cstrip}\right) \cdot 3m \cdot d_{eff.column.y.cstrip}{}^{2} \cdot f_{cd} = -426.72 \cdot$$

$$M_{Rd.span.y.cstrip} := 0.8 \cdot \alpha_{span.y.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.y.cstrip}\right) \cdot 3m \cdot d_{eff.span.y.cstrip}{}^{2} \cdot f_{cd} = 422.92 \cdot kN \cdot m$$

$$M_{Rd.column.y.mstrip} := -0.8 \cdot \alpha_{column.y.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.y.mstrip}\right) \cdot 6m \cdot d_{eff.column.y.mstrip}{}^{2} \cdot f_{cd} = -103.4$$

$$M_{Rd.span.y.mstrip} := 0.8 \cdot \alpha_{span.y.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.y.mstrip}\right) \cdot 6m \cdot d_{eff.span.y.mstrip}{}^{2} \cdot f_{cd} = 180.98 \cdot kN \cdot m$$

	X-direction				Y-direction			
	Column strip		Middle strip		Column strip		Middle strip	
	At column	At span	At column	At span	At column	At span	At column	At span
MEd	-363.8	298.8	-173	191	-241.8	199	-134.9	115.9
MRd	-426.5	428	-64.6	95.6	-426.7	422.9	-103.4	181
Utilization	85 %	70 %	268 %	200 %	57 %	47 %	130 %	64 %

Tendon layout C

$N_{x.cstrip} := 6$ Number of tendons in interior strip x-direction, column strip

$N_{x.mstrip} := 6$ Number of tendons in interior strip x-direction, middle strip

$N_{y.cstrip} := 12$ Number of tendons in interior strip y-direction, column strip

$N_{y.mstrip} := 0$ Number of tendons in interior strip y-direction, middle strip

$$q_{p.x.cstrip} := \frac{N_{x.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 8.15 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, column strip

$$q_{p.x.mstrip} := \frac{N_{x.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 8.15 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, middle strip

$$q_{p.y.cstrip} := \frac{N_{y.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 36.66 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, column strip

$$q_{p.y.mstrip} := \frac{N_{y.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, middle strip

$M_{p.column.x.cstrip} := 0.1 \cdot q_{p.x.cstrip} \cdot span_x^2 = 66 \cdot kN \cdot m$ Prestressing moment at column, x-direction, column strip

$M_{p.span.x.cstrip} := -0.08 \cdot q_{p.x.cstrip} \cdot span_x^2 = -52.8 \cdot kN \cdot m$ Prestressing moment in span, x-direction, column strip

$M_{p.column.x.mstrip} := 0.1 \cdot q_{p.x.mstrip} \cdot span_x^2 = 66 \cdot kN \cdot m$ Prestressing moment at column, x-direction, middle strip

$M_{p.span.x.mstrip} := -0.08 \cdot q_{p.x.mstrip} \cdot span_x^2 = -52.8 \cdot kN \cdot m$ Prestressing moment in span, x-direction, middle strip

$M_{p.column.y.cstrip} := 0.125 \cdot q_{p.y.cstrip} \cdot span_y^2 = 164.99 \cdot kN \cdot m$ Prestressing moment at column, y-direction, column strip

$M_{p.span.y.cstrip} := -0.0703 \cdot q_{p.y.cstrip} \cdot span_y^2 = -92.79 \cdot kN \cdot m$ Prestressing moment in span, y-direction, column strip

$M_{p.column.y.mstrip} := 0.125 \cdot q_{p.y.mstrip} \cdot span_y^2 = 0 \cdot kN \cdot m$ Prestressing moment at column, y-direction, middle strip

$M_{p.span.y.mstrip} := -0.0703 \cdot q_{p.y.mstrip} \cdot span_y^2 = 0 \cdot kN \cdot m$ Prestressing moment in span, y-direction, middle strip

$M_{0.column.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot e_{top} = 46.07 \cdot kN \cdot m$ Primary moment at column, x-direction, column strip

$M_{0.span.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -58.92 \cdot kN \cdot m$ Primary moment in span, x-direction, column strip

$M_{0.column.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot e_{top} = 46.07 \cdot kN \cdot m$ Primary moment at column, x-direction, middle strip

$M_{0.span.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot -e_{bottom} = -58.92 \cdot kN \cdot m$ Primary moment in span, x-direction, middle strip

$M_{0.column.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot e_{top} = 92.14 \cdot kN \cdot m$ Primary moment at column, y-direction, column strip

$M_{0.span.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -117.85 \cdot kN \cdot m$ Primary moment in span, y-direction, column strip

$M_{0.column.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, y-direction, middle strip

$M_{0.span.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, y-direction, middle strip

Characteristic hyperstatic moments:

$M_{Ek.h.column.x.cstrip} := M_{p.column.x.cstrip} - M_{0.column.x.cstrip} = 19.93 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.span.x.cstrip} := M_{p.span.x.cstrip} - M_{0.span.x.cstrip} = 6.13 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.column.x.mstrip} := M_{p.column.x.mstrip} - M_{0.column.x.mstrip} = 19.93 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.span.x.mstrip} := M_{p.span.x.mstrip} - M_{0.span.x.mstrip} = 6.13 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.column.y.cstrip} := M_{p.column.y.cstrip} - M_{0.column.y.cstrip} = 72.85 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.span.y.cstrip} := M_{p.span.y.cstrip} - M_{0.span.y.cstrip} = 25.06 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.column.y.mstrip} := M_{p.column.y.mstrip} - M_{0.column.y.mstrip} = 0 \cdot kN \cdot m$ y-direction, middle strip

$M_{Ek.h.span.y.mstrip} := M_{p.span.y.mstrip} - M_{0.span.y.mstrip} = 0 \cdot kN \cdot m$ y-direction, middle strip

Design moments:

$$M_{Ed.column.x.cstrip} := \gamma_g \cdot M_{Ek.g.column.x.cstrip} + \gamma_q \cdot M_{Ek.q.column.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.cstrip} = -383.72 \cdot kN \cdot m$$

$$M_{Ed.span.x.cstrip} := \gamma_g \cdot M_{Ek.g.span.x.cstrip} + \gamma_q \cdot M_{Ek.q.span.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.cstrip} = 292.63 \cdot kN \cdot m$$

$$M_{Ed.column.x.mstrip} := \gamma_g \cdot M_{Ek.g.column.x.mstrip} + \gamma_q \cdot M_{Ek.q.column.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.mstrip} = -153.06 \cdot kN \cdot m$$

$$M_{Ed.span.x.mstrip} := \gamma_g \cdot M_{Ek.g.span.x.mstrip} + \gamma_q \cdot M_{Ek.q.span.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.mstrip} = 197.13 \cdot kN \cdot m$$

$$M_{Ed.column.y.cstrip} := \gamma_g \cdot M_{Ek.g.column.y.cstrip} + \gamma_q \cdot M_{Ek.q.column.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.cstrip} = -241.83 \cdot kN \cdot m$$

$$M_{Ed.span.y.cstrip} := \gamma_g \cdot M_{Ek.g.span.y.cstrip} + \gamma_q \cdot M_{Ek.q.span.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.cstrip} = 198.98 \cdot kN \cdot m$$

$$M_{Ed.column.y.mstrip} := \gamma_g \cdot M_{Ek.g.column.y.mstrip} + \gamma_q \cdot M_{Ek.q.column.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.mstrip} = -134.87 \cdot kN \cdot m$$

$$M_{Ed.span.y.mstrip} := \gamma_g \cdot M_{Ek.g.span.y.mstrip} + \gamma_q \cdot M_{Ek.q.span.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.mstrip} = 115.94 \cdot kN \cdot m$$

$S_{p.x.cstrip} := N_{x.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 1.16 \times 10^3 \cdot kN$

Forces in tendons, x-direction, column strip

$S_{p.x.mstrip} := N_{x.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 1.16 \times 10^3 \cdot kN$

Forces in tendons, x-direction, middle strip

$S_{p.y.cstrip} := N_{y.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 2.32 \times 10^3 \cdot kN$

Forces in tendons, y-direction, column strip

$S_{p.y.mstrip} := N_{y.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$

Forces in tendons, y-direction, middle strip

Effective slab thicknesses:

$$d_{eff.column.x.cstrip} := \frac{d_{p.column} \cdot S_{p.x.cstrip} + d_{d.column.x} \cdot S_{d.top.x.cstrip}}{S_{p.x.cstrip} + S_{d.top.x.cstrip}} = 165.78 \cdot mm$$

$$d_{eff.span.x.cstrip} := \frac{d_{p.span} \cdot S_{p.x.cstrip} + d_{d.span.x} \cdot S_{d.btm.x.cstrip}}{S_{p.x.cstrip} + S_{d.btm.x.cstrip}} = 172.65 \cdot mm$$

$$d_{eff.column.x.mstrip} := \frac{d_{p.column} \cdot S_{p.x.mstrip} + d_{d.column.x} \cdot S_{d.top.x.mstrip}}{S_{p.x.mstrip} + S_{d.top.x.mstrip}} = 160.87 \cdot mm$$

$$d_{eff.span.x.mstrip} := \frac{d_{p.span} \cdot S_{p.x.mstrip} + d_{d.span.x} \cdot S_{d.btm.x.mstrip}}{S_{p.x.mstrip} + S_{d.btm.x.mstrip}} = 172.65 \cdot mm$$

$$d_{eff.column.y.cstrip} := \frac{d_{p.column} \cdot S_{p.y.cstrip} + d_{d.column.y} \cdot S_{d.top.y.cstrip}}{S_{p.y.cstrip} + S_{d.top.y.cstrip}} = 157.55 \cdot mm$$

$$d_{eff.span.y.cstrip} := \frac{d_{p.span} \cdot S_{p.y.cstrip} + d_{d.span.y} \cdot S_{d.btm.y.cstrip}}{S_{p.y.cstrip} + S_{d.btm.y.cstrip}} = 167.71 \cdot mm$$

$$d_{eff.column.y.mstrip} := \frac{d_{p.column} \cdot S_{p.y.mstrip} + d_{d.column.y} \cdot S_{d.top.y.mstrip}}{S_{p.y.mstrip} + S_{d.top.y.mstrip}} = 171 \cdot mm$$

$$d_{eff.span.y.mstrip} := \frac{d_{p.span} \cdot S_{p.y.mstrip} + d_{d.span.y} \cdot S_{d.btm.y.mstrip}}{S_{p.y.mstrip} + S_{d.btm.y.mstrip}} = 180 \cdot mm$$

α-factors:

$$\alpha_{column.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.top.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.cstrip}} = 0.18$$

$$\alpha_{span.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.btm.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.cstrip}} = 0.16$$

$$\alpha_{column.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.top.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.mstrip}} = 0.15$$

$$\alpha_{span.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.btm.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.mstrip}} = 0.16$$

$$\alpha_{column.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.top.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.y.cstrip}} = 0.32$$

$$\alpha_{span.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.btm.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.y.cstrip}} = 0.28$$

$$\alpha_{column.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.top.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.column.y.mstrip}} = 0.03$$

$$\alpha_{span.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.btm.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.span.y.mstrip}} = 0.05$$

Moment capacities:

$$M_{Rd.column.x.cstrip} := -0.8\cdot\alpha_{column.x.cstrip}\cdot\left(1-0.4\cdot\alpha_{column.x.cstrip}\right)\cdot 3m\cdot d_{eff.column.x.cstrip}{}^{2}\cdot f_{cd} = -285.84\cdot$$

$$M_{Rd.span.x.cstrip} := 0.8\cdot\alpha_{span.x.cstrip}\cdot\left(1-0.4\cdot\alpha_{span.x.cstrip}\right)\cdot 3m\cdot d_{eff.span.x.cstrip}{}^{2}\cdot f_{cd} = 270.64\cdot kN\cdot m$$

$$M_{Rd.column.x.mstrip} := -0.8\cdot\alpha_{column.x.mstrip}\cdot\left(1-0.4\cdot\alpha_{column.x.mstrip}\right)\cdot 3m\cdot d_{eff.column.x.mstrip}{}^{2}\cdot f_{cd} = -228.$$

$$M_{Rd.span.x.mstrip} := 0.8\cdot\alpha_{span.x.mstrip}\cdot\left(1-0.4\cdot\alpha_{span.x.mstrip}\right)\cdot 3m\cdot d_{eff.span.x.mstrip}{}^{2}\cdot f_{cd} = 270.64\cdot kN\cdot m$$

$$M_{Rd.column.y.cstrip} := -0.8\cdot\alpha_{column.y.cstrip}\cdot\left(1-0.4\cdot\alpha_{column.y.cstrip}\right)\cdot 3m\cdot d_{eff.column.y.cstrip}{}^{2}\cdot f_{cd} = -426.72\cdot$$

$$M_{Rd.span.y.cstrip} := 0.8\cdot\alpha_{span.y.cstrip}\cdot\left(1-0.4\cdot\alpha_{span.y.cstrip}\right)\cdot 3m\cdot d_{eff.span.y.cstrip}{}^{2}\cdot f_{cd} = 422.92\cdot kN\cdot m$$

$$M_{Rd.column.y.mstrip} := -0.8\cdot\alpha_{column.y.mstrip}\cdot\left(1-0.4\cdot\alpha_{column.y.mstrip}\right)\cdot 6m\cdot d_{eff.column.y.mstrip}{}^{2}\cdot f_{cd} = -103.4$$

$$M_{Rd.span.y.mstrip} := 0.8\cdot\alpha_{span.y.mstrip}\cdot\left(1-0.4\cdot\alpha_{span.y.mstrip}\right)\cdot 6m\cdot d_{eff.span.y.mstrip}{}^{2}\cdot f_{cd} = 180.98\cdot kN\cdot m$$

	X-direction				Y-direction			
	Column strip		Middle strip		Column strip		Middle strip	
	At column	At span	At column	At span	At column	At span	At column	At span
MEd	-383.7	292.6	-153.1	197.1	-241.8	199	-134.9	115.9
MRd	-285.8	270.6	-228.2	270.6	-426.7	422.9	-103.4	181
Utilization	134 %	108 %	67 %	73 %	57 %	47 %	130 %	64 %

Tendon layout D

$N_{x.cstrip} := 8$ Number of tendons in interior strip x-direction, column strip

$N_{x.mstrip} := 4$ Number of tendons in interior strip x-direction, middle strip

$N_{y.cstrip} := 12$ Number of tendons in interior strip y-direction, column strip

$N_{y.mstrip} := 0$ Number of tendons in interior strip y-direction, middle strip

$$q_{p.x.cstrip} := \frac{N_{x.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 10.86 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, column strip

$$q_{p.x.mstrip} := \frac{N_{x.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 5.43 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, middle strip

$$q_{p.y.cstrip} := \frac{N_{y.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 36.66 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, column strip

$$q_{p.y.mstrip} := \frac{N_{y.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, middle strip

$M_{p.column.x.cstrip} := 0.1 \cdot q_{p.x.cstrip} \cdot span_x^2 = 87.99 \cdot kN \cdot m$ — Prestressing moment at column, x-direction, column strip

$M_{p.span.x.cstrip} := -0.08 \cdot q_{p.x.cstrip} \cdot span_x^2 = -70.4 \cdot kN \cdot m$ — Prestressing moment in span, x-direction, column strip

$M_{p.column.x.mstrip} := 0.1 \cdot q_{p.x.mstrip} \cdot span_x^2 = 44 \cdot kN \cdot m$ — Prestressing moment at column, x-direction, middle strip

$M_{p.span.x.mstrip} := -0.08 \cdot q_{p.x.mstrip} \cdot span_x^2 = -35.2 \cdot kN \cdot m$ — Prestressing moment in span, x-direction, middle strip

$M_{p.column.y.cstrip} := 0.125 \cdot q_{p.y.cstrip} \cdot span_y^2 = 164.99 \cdot kN \cdot m$ — Prestressing moment at column, y-direction, column strip

$M_{p.span.y.cstrip} := -0.0703 \cdot q_{p.y.cstrip} \cdot span_y^2 = -92.79 \cdot kN \cdot m$ — Prestressing moment in span, y-direction, column strip

$M_{p.column.y.mstrip} := 0.125 \cdot q_{p.y.mstrip} \cdot span_y^2 = 0 \cdot kN \cdot m$ — Prestressing moment at column, y-direction, middle strip

$M_{p.span.y.mstrip} := -0.0703 \cdot q_{p.y.mstrip} \cdot span_y^2 = 0 \cdot kN \cdot m$ — Prestressing moment in span, y-direction, middle strip

$M_{0.column.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot e_{top} = 61.42 \cdot kN \cdot m$ — Primary moment at column, x-direction, column strip

$M_{0.span.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -78.57 \cdot kN \cdot m$ — Primary moment in span, x-direction, column strip

$M_{0.column.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot e_{top} = 30.71 \cdot kN \cdot m$ — Primary moment at column, x-direction, middle strip

$M_{0.span.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot -e_{bottom} = -39.28 \cdot kN \cdot m$ — Primary moment in span, x-direction, middle strip

$M_{0.column.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot e_{top} = 92.14 \cdot kN \cdot m$ — Primary moment at column, y-direction, column strip

$M_{0.span.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -117.85 \cdot kN \cdot m$ — Primary moment in span, y-direction, column strip

$M_{0.column.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ — Primary moment at column, y-direction, middle strip

$M_{0.span.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ — Primary moment in span, y-direction, middle strip

Characteristic hyperstatic moments:

$$M_{Ek.h.column.x.cstrip} := M_{p.column.x.cstrip} - M_{0.column.x.cstrip} = 26.57 \cdot kN \cdot m$$ x-direction, column strip

$$M_{Ek.h.span.x.cstrip} := M_{p.span.x.cstrip} - M_{0.span.x.cstrip} = 8.17 \cdot kN \cdot m$$ x-direction, column strip

$$M_{Ek.h.column.x.mstrip} := M_{p.column.x.mstrip} - M_{0.column.x.mstrip} = 13.28 \cdot kN \cdot m$$ x-direction, middle strip

$$M_{Ek.h.span.x.mstrip} := M_{p.span.x.mstrip} - M_{0.span.x.mstrip} = 4.09 \cdot kN \cdot m$$ x-direction, middle strip

$$M_{Ek.h.column.y.cstrip} := M_{p.column.y.cstrip} - M_{0.column.y.cstrip} = 72.85 \cdot kN \cdot m$$ y-direction, column strip

$$M_{Ek.h.span.y.cstrip} := M_{p.span.y.cstrip} - M_{0.span.y.cstrip} = 25.06 \cdot kN \cdot m$$ y-direction, column strip

$$M_{Ek.h.column.y.mstrip} := M_{p.column.y.mstrip} - M_{0.column.y.mstrip} = 0 \cdot kN \cdot m$$ y-direction, middle strip

$$M_{Ek.h.span.y.mstrip} := M_{p.span.y.mstrip} - M_{0.span.y.mstrip} = 0 \cdot kN \cdot m$$ y-direction, middle strip

Design moments:

$$M_{Ed.column.x.cstrip} := \gamma_g \cdot M_{Ek.g.column.x.cstrip} + \gamma_q \cdot M_{Ek.q.column.x.cstrip} \dots + \gamma_p \cdot M_{Ek.h.column.x.cstrip} = -377.08 \cdot kN \cdot m$$

$$M_{Ed.span.x.cstrip} := \gamma_g \cdot M_{Ek.g.span.x.cstrip} + \gamma_q \cdot M_{Ek.q.span.x.cstrip} \dots + \gamma_p \cdot M_{Ek.h.span.x.cstrip} = 294.67 \cdot kN \cdot m$$

$$M_{Ed.column.x.mstrip} := \gamma_g \cdot M_{Ek.g.column.x.mstrip} + \gamma_q \cdot M_{Ek.q.column.x.mstrip} \dots + \gamma_p \cdot M_{Ek.h.column.x.mstrip} = -159.71 \cdot kN \cdot m$$

$$M_{Ed.span.x.mstrip} := \gamma_g \cdot M_{Ek.g.span.x.mstrip} + \gamma_q \cdot M_{Ek.q.span.x.mstrip} \dots + \gamma_p \cdot M_{Ek.h.span.x.mstrip} = 195.08 \cdot kN \cdot m$$

$$M_{Ed.column.y.cstrip} := \gamma_g \cdot M_{Ek.g.column.y.cstrip} + \gamma_q \cdot M_{Ek.q.column.y.cstrip} \dots + \gamma_p \cdot M_{Ek.h.column.y.cstrip} = -241.83 \cdot kN \cdot m$$

$$M_{Ed.span.y.cstrip} := \gamma_g \cdot M_{Ek.g.span.y.cstrip} + \gamma_q \cdot M_{Ek.q.span.y.cstrip} \dots + \gamma_p \cdot M_{Ek.h.span.y.cstrip} = 198.98 \cdot kN \cdot m$$

$$M_{Ed.column.y.mstrip} := \gamma_g \cdot M_{Ek.g.column.y.mstrip} + \gamma_q \cdot M_{Ek.q.column.y.mstrip} \dots + \gamma_p \cdot M_{Ek.h.column.y.mstrip} = -134.87 \cdot kN \cdot m$$

$$M_{Ed.span.y.mstrip} := \gamma_g \cdot M_{Ek.g.span.y.mstrip} + \gamma_q \cdot M_{Ek.q.span.y.mstrip} \dots + \gamma_p \cdot M_{Ek.h.span.y.mstrip} = 115.94 \cdot kN \cdot m$$

$S_{p.x.cstrip} := N_{x.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 1.55 \times 10^3 \cdot kN$

Forces in tendons, x-direction, column strip

$S_{p.x.mstrip} := N_{x.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 774.24 \cdot kN$

Forces in tendons, x-direction, middle strip

$S_{p.y.cstrip} := N_{y.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 2.32 \times 10^3 \cdot kN$

Forces in tendons, y-direction, column strip

$S_{p.y.mstrip} := N_{y.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$

Forces in tendons, y-direction, middle strip

Effective slab thicknesses:

$$d_{eff.column.x.cstrip} := \frac{d_{p.column} \cdot S_{p.x.cstrip} + d_{d.column.x} \cdot S_{d.top.x.cstrip}}{S_{p.x.cstrip} + S_{d.top.x.cstrip}} = 163.58 \cdot mm$$

$$d_{eff.span.x.cstrip} := \frac{d_{p.span} \cdot S_{p.x.cstrip} + d_{d.span.x} \cdot S_{d.btm.x.cstrip}}{S_{p.x.cstrip} + S_{d.btm.x.cstrip}} = 171.21 \cdot mm$$

$$d_{eff.column.x.mstrip} := \frac{d_{p.column} \cdot S_{p.x.mstrip} + d_{d.column.x} \cdot S_{d.top.x.mstrip}}{S_{p.x.mstrip} + S_{d.top.x.mstrip}} = 163.58 \cdot mm$$

$$d_{eff.span.x.mstrip} := \frac{d_{p.span} \cdot S_{p.x.mstrip} + d_{d.span.x} \cdot S_{d.btm.x.mstrip}}{S_{p.x.mstrip} + S_{d.btm.x.mstrip}} = 174.95 \cdot mm$$

$$d_{eff.column.y.cstrip} := \frac{d_{p.column} \cdot S_{p.y.cstrip} + d_{d.column.y} \cdot S_{d.top.y.cstrip}}{S_{p.y.cstrip} + S_{d.top.y.cstrip}} = 157.55 \cdot mm$$

$$d_{eff.span.y.cstrip} := \frac{d_{p.span} \cdot S_{p.y.cstrip} + d_{d.span.y} \cdot S_{d.btm.y.cstrip}}{S_{p.y.cstrip} + S_{d.btm.y.cstrip}} = 167.71 \cdot mm$$

$$d_{eff.column.y.mstrip} := \frac{d_{p.column} \cdot S_{p.y.mstrip} + d_{d.column.y} \cdot S_{d.top.y.mstrip}}{S_{p.y.mstrip} + S_{d.top.y.mstrip}} = 171 \cdot mm$$

$$d_{eff.span.y.mstrip} := \frac{d_{p.span} \cdot S_{p.y.mstrip} + d_{d.span.y} \cdot S_{d.btm.y.mstrip}}{S_{p.y.mstrip} + S_{d.btm.y.mstrip}} = 180 \cdot mm$$

α-factors:

$$\alpha_{column.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.top.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.cstrip}} = 0.22$$

$$\alpha_{span.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.btm.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.cstrip}} = 0.2$$

$$\alpha_{column.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.top.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.mstrip}} = 0.11$$

$$\alpha_{span.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.btm.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.mstrip}} = 0.12$$

$$\alpha_{column.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.top.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.y.cstrip}} = 0.32$$

$$\alpha_{span.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.btm.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.y.cstrip}} = 0.28$$

$$\alpha_{column.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.top.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.column.y.mstrip}} = 0.03$$

$$\alpha_{span.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.btm.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.span.y.mstrip}} = 0.05$$

Moment capacities:

$$M_{Rd.column.x.cstrip} := -0.8 \cdot \alpha_{column.x.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.x.cstrip}\right) \cdot 3m \cdot d_{eff.column.x.cstrip}{}^{2} \cdot f_{cd} = -334.68 \cdot$$

$$M_{Rd.span.x.cstrip} := 0.8 \cdot \alpha_{span.x.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.x.cstrip}\right) \cdot 3m \cdot d_{eff.span.x.cstrip}{}^{2} \cdot f_{cd} = 325.07 \cdot kN \cdot m$$

$$M_{Rd.column.x.mstrip} := -0.8 \cdot \alpha_{column.x.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.x.mstrip}\right) \cdot 3m \cdot d_{eff.column.x.mstrip}{}^{2} \cdot f_{cd} = -175.$$

$$M_{Rd.span.x.mstrip} := 0.8 \cdot \alpha_{span.x.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.x.mstrip}\right) \cdot 3m \cdot d_{eff.span.x.mstrip}{}^{2} \cdot f_{cd} = 214.26 \cdot kN \cdot m$$

$$M_{Rd.column.y.cstrip} := -0.8 \cdot \alpha_{column.y.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.y.cstrip}\right) \cdot 3m \cdot d_{eff.column.y.cstrip}{}^{2} \cdot f_{cd} = -426.72 \cdot$$

$$M_{Rd.span.y.cstrip} := 0.8 \cdot \alpha_{span.y.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.y.cstrip}\right) \cdot 3m \cdot d_{eff.span.y.cstrip}{}^{2} \cdot f_{cd} = 422.92 \cdot kN \cdot m$$

$$M_{Rd.column.y.mstrip} := -0.8 \cdot \alpha_{column.y.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.y.mstrip}\right) \cdot 6m \cdot d_{eff.column.y.mstrip}{}^{2} \cdot f_{cd} = -103.4$$

$$M_{Rd.span.y.mstrip} := 0.8 \cdot \alpha_{span.y.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.y.mstrip}\right) \cdot 6m \cdot d_{eff.span.y.mstrip}{}^{2} \cdot f_{cd} = 180.98 \cdot kN \cdot m$$

	X-direction				Y-direction			
	Column strip		Middle strip		Column strip		Middle strip	
	At column	At span	At column	At span	At column	At span	At column	At span
MEd	-377.1	294.7	-159.7	195.1	-241.8	199	-134.9	115.9
MRd	-334.7	325.1	-175.6	214.3	-426.7	422.9	-103.4	181
Utilization	113 %	91 %	91 %	91 %	57 %	47 %	130 %	64 %

Tendon layout E

$N_{x.cstrip} := 8$ Number of tendons in interior strip x-direction, column strip

$N_{x.mstrip} := 4$ Number of tendons in interior strip x-direction, middle strip

$N_{y.cstrip} := 8$ Number of tendons in interior strip y-direction, column strip

$N_{y.mstrip} := 4$ Number of tendons in interior strip y-direction, middle strip

$$q_{p.x.cstrip} := \frac{N_{x.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 10.86 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, column strip

$$q_{p.x.mstrip} := \frac{N_{x.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^2} = 5.43 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, middle strip

$$q_{p.y.cstrip} := \frac{N_{y.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 24.44 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, column strip

$$q_{p.y.mstrip} := \frac{N_{y.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^2} = 12.22 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, middle strip

$M_{p.column.x.cstrip} := 0.1 \cdot q_{p.x.cstrip} \cdot span_x^2 = 87.99 \cdot kN \cdot m$ — Prestressing moment at column, x-direction, column strip

$M_{p.span.x.cstrip} := -0.08 \cdot q_{p.x.cstrip} \cdot span_x^2 = -70.4 \cdot kN \cdot m$ — Prestressing moment in span, x-direction, column strip

$M_{p.column.x.mstrip} := 0.1 \cdot q_{p.x.mstrip} \cdot span_x^2 = 44 \cdot kN \cdot m$ — Prestressing moment at column, x-direction, middle strip

$M_{p.span.x.mstrip} := -0.08 \cdot q_{p.x.mstrip} \cdot span_x^2 = -35.2 \cdot kN \cdot m$ — Prestressing moment in span, x-direction, middle strip

$M_{p.column.y.cstrip} := 0.125 \cdot q_{p.y.cstrip} \cdot span_y^2 = 109.99 \cdot kN \cdot m$ — Prestressing moment at column, y-direction, column strip

$M_{p.span.y.cstrip} := -0.0703 \cdot q_{p.y.cstrip} \cdot span_y^2 = -61.86 \cdot kN \cdot m$ — Prestressing moment in span, y-direction, column strip

$M_{p.column.y.mstrip} := 0.125 \cdot q_{p.y.mstrip} \cdot span_y^2 = 55 \cdot kN \cdot m$ — Prestressing moment at column, y-direction, middle strip

$M_{p.span.y.mstrip} := -0.0703 \cdot q_{p.y.mstrip} \cdot span_y^2 = -30.93 \cdot kN \cdot m$ — Prestressing moment in span, y-direction, middle strip

$M_{0.column.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot e_{top} = 61.42 \cdot kN \cdot m$ — Primary moment at column, x-direction, column strip

$M_{0.span.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -78.57 \cdot kN \cdot m$ — Primary moment in span, x-direction, column strip

$M_{0.column.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot e_{top} = 30.71 \cdot kN \cdot m$ — Primary moment at column, x-direction, middle strip

$M_{0.span.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot -e_{bottom} = -39.28 \cdot kN \cdot m$ — Primary moment in span, x-direction, middle strip

$M_{0.column.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot e_{top} = 61.42 \cdot kN \cdot m$ — Primary moment at column, y-direction, column strip

$M_{0.span.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot -e_{bottom} = -78.57 \cdot kN \cdot m$ — Primary moment in span, y-direction, column strip

$M_{0.column.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot e_{top} = 30.71 \cdot kN \cdot m$ — Primary moment at column, y-direction, middle strip

$M_{0.span.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot -e_{bottom} = -39.28 \cdot kN \cdot m$ — Primary moment in span, y-direction, middle strip

Characteristic hyperstatic moments:

$M_{Ek.h.column.x.cstrip} := M_{p.column.x.cstrip} - M_{0.column.x.cstrip} = 26.57 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.span.x.cstrip} := M_{p.span.x.cstrip} - M_{0.span.x.cstrip} = 8.17 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.column.x.mstrip} := M_{p.column.x.mstrip} - M_{0.column.x.mstrip} = 13.28 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.span.x.mstrip} := M_{p.span.x.mstrip} - M_{0.span.x.mstrip} = 4.09 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.column.y.cstrip} := M_{p.column.y.cstrip} - M_{0.column.y.cstrip} = 48.57 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.span.y.cstrip} := M_{p.span.y.cstrip} - M_{0.span.y.cstrip} = 16.71 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.column.y.mstrip} := M_{p.column.y.mstrip} - M_{0.column.y.mstrip} = 24.28 \cdot kN \cdot m$ y-direction, middle strip

$M_{Ek.h.span.y.mstrip} := M_{p.span.y.mstrip} - M_{0.span.y.mstrip} = 8.35 \cdot kN \cdot m$ y-direction, middle strip

Design moments:

$$M_{Ed.column.x.cstrip} := \gamma_g \cdot M_{Ek.g.column.x.cstrip} + \gamma_q \cdot M_{Ek.q.column.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.cstrip} = -377.08 \cdot kN \cdot m$$

$$M_{Ed.span.x.cstrip} := \gamma_g \cdot M_{Ek.g.span.x.cstrip} + \gamma_q \cdot M_{Ek.q.span.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.cstrip} = 294.67 \cdot kN \cdot m$$

$$M_{Ed.column.x.mstrip} := \gamma_g \cdot M_{Ek.g.column.x.mstrip} + \gamma_q \cdot M_{Ek.q.column.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.mstrip} = -159.71 \cdot kN \cdot m$$

$$M_{Ed.span.x.mstrip} := \gamma_g \cdot M_{Ek.g.span.x.mstrip} + \gamma_q \cdot M_{Ek.q.span.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.mstrip} = 195.08 \cdot kN \cdot m$$

$$M_{Ed.column.y.cstrip} := \gamma_g \cdot M_{Ek.g.column.y.cstrip} + \gamma_q \cdot M_{Ek.q.column.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.cstrip} = -266.12 \cdot kN \cdot m$$

$$M_{Ed.span.y.cstrip} := \gamma_g \cdot M_{Ek.g.span.y.cstrip} + \gamma_q \cdot M_{Ek.q.span.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.cstrip} = 190.62 \cdot kN \cdot m$$

$$M_{Ed.column.y.mstrip} := \gamma_g \cdot M_{Ek.g.column.y.mstrip} + \gamma_q \cdot M_{Ek.q.column.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.mstrip} = -110.58 \cdot kN \cdot m$$

$$M_{Ed.span.y.mstrip} := \gamma_g \cdot M_{Ek.g.span.y.mstrip} + \gamma_q \cdot M_{Ek.q.span.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.mstrip} = 124.3 \cdot kN \cdot m$$

$$S_{p.x.cstrip} := N_{x.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 1.55 \times 10^3 \cdot kN$$

Forces in tendons, x-direction, column strip

$$S_{p.x.mstrip} := N_{x.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 774.24 \cdot kN$$

Forces in tendons, x-direction, middle strip

$$S_{p.y.cstrip} := N_{y.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 1.55 \times 10^3 \cdot kN$$

Forces in tendons, y-direction, column strip

$$S_{p.y.mstrip} := N_{y.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 774.24 \cdot kN$$

Forces in tendons, y-direction, middle strip

Effective slab thicknesses:

$$d_{eff.column.x.cstrip} := \frac{d_{p.column} \cdot S_{p.x.cstrip} + d_{d.column.x} \cdot S_{d.top.x.cstrip}}{S_{p.x.cstrip} + S_{d.top.x.cstrip}} = 163.58 \cdot mm$$

$$d_{eff.span.x.cstrip} := \frac{d_{p.span} \cdot S_{p.x.cstrip} + d_{d.span.x} \cdot S_{d.btm.x.cstrip}}{S_{p.x.cstrip} + S_{d.btm.x.cstrip}} = 171.21 \cdot mm$$

$$d_{eff.column.x.mstrip} := \frac{d_{p.column} \cdot S_{p.x.mstrip} + d_{d.column.x} \cdot S_{d.top.x.mstrip}}{S_{p.x.mstrip} + S_{d.top.x.mstrip}} = 163.58 \cdot mm$$

$$d_{eff.span.x.mstrip} := \frac{d_{p.span} \cdot S_{p.x.mstrip} + d_{d.span.x} \cdot S_{d.btm.x.mstrip}}{S_{p.x.mstrip} + S_{d.btm.x.mstrip}} = 174.95 \cdot mm$$

$$d_{eff.column.y.cstrip} := \frac{d_{p.column} \cdot S_{p.y.cstrip} + d_{d.column.y} \cdot S_{d.top.y.cstrip}}{S_{p.y.cstrip} + S_{d.top.y.cstrip}} = 159.06 \cdot mm$$

$$d_{eff.span.y.cstrip} := \frac{d_{p.span} \cdot S_{p.y.cstrip} + d_{d.span.y} \cdot S_{d.btm.y.cstrip}}{S_{p.y.cstrip} + S_{d.btm.y.cstrip}} = 168.73 \cdot mm$$

$$d_{eff.column.y.mstrip} := \frac{d_{p.column} \cdot S_{p.y.mstrip} + d_{d.column.y} \cdot S_{d.top.y.mstrip}}{S_{p.y.mstrip} + S_{d.top.y.mstrip}} = 160.95 \cdot mm$$

$$d_{eff.span.y.mstrip} := \frac{d_{p.span} \cdot S_{p.y.mstrip} + d_{d.span.y} \cdot S_{d.btm.y.mstrip}}{S_{p.y.mstrip} + S_{d.btm.y.mstrip}} = 173.54 \cdot mm$$

α-factors:

$$\alpha_{column.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.top.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.cstrip}} = 0.22$$

$$\alpha_{span.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.btm.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.cstrip}} = 0.2$$

$$\alpha_{column.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.top.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.mstrip}} = 0.11$$

$$\alpha_{span.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.btm.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.mstrip}} = 0.12$$

$$\alpha_{column.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.top.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.y.cstrip}} = 0.24$$

$$\alpha_{span.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.btm.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.y.cstrip}} = 0.2$$

$$\alpha_{column.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.top.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.column.y.mstrip}} = 0.07$$

$$\alpha_{span.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.btm.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.span.y.mstrip}} = 0.08$$

Moment capacities:

$$M_{Rd.column.x.cstrip} := -0.8\cdot\alpha_{column.x.cstrip}\cdot\left(1-0.4\cdot\alpha_{column.x.cstrip}\right)\cdot 3m\cdot d_{eff.column.x.cstrip}{}^{2}\cdot f_{cd} = -334.68\cdot$$

$$M_{Rd.span.x.cstrip} := 0.8\cdot\alpha_{span.x.cstrip}\cdot\left(1-0.4\cdot\alpha_{span.x.cstrip}\right)\cdot 3m\cdot d_{eff.span.x.cstrip}{}^{2}\cdot f_{cd} = 325.07\cdot kN\cdot m$$

$$M_{Rd.column.x.mstrip} := -0.8\cdot\alpha_{column.x.mstrip}\cdot\left(1-0.4\cdot\alpha_{column.x.mstrip}\right)\cdot 3m\cdot d_{eff.column.x.mstrip}{}^{2}\cdot f_{cd} = -175.$$

$$M_{Rd.span.x.mstrip} := 0.8\cdot\alpha_{span.x.mstrip}\cdot\left(1-0.4\cdot\alpha_{span.x.mstrip}\right)\cdot 3m\cdot d_{eff.span.x.mstrip}{}^{2}\cdot f_{cd} = 214.26\cdot kN\cdot m$$

$$M_{Rd.column.y.cstrip} := -0.8\cdot\alpha_{column.y.cstrip}\cdot\left(1-0.4\cdot\alpha_{column.y.cstrip}\right)\cdot 3m\cdot d_{eff.column.y.cstrip}{}^{2}\cdot f_{cd} = -335.82\cdot$$

$$M_{Rd.span.y.cstrip} := 0.8\cdot\alpha_{span.y.cstrip}\cdot\left(1-0.4\cdot\alpha_{span.y.cstrip}\right)\cdot 3m\cdot d_{eff.span.y.cstrip}{}^{2}\cdot f_{cd} = 319.95\cdot kN\cdot m$$

$$M_{Rd.column.y.mstrip} := -0.8\cdot\alpha_{column.y.mstrip}\cdot\left(1-0.4\cdot\alpha_{column.y.mstrip}\right)\cdot 6m\cdot d_{eff.column.y.mstrip}{}^{2}\cdot f_{cd} = -216.8$$

$$M_{Rd.span.y.mstrip} := 0.8\cdot\alpha_{span.y.mstrip}\cdot\left(1-0.4\cdot\alpha_{span.y.mstrip}\right)\cdot 6m\cdot d_{eff.span.y.mstrip}{}^{2}\cdot f_{cd} = 301.58\cdot kN\cdot m$$

	X-direction				Y-direction			
	Column strip		Middle strip		Column strip		Middle strip	
	At column	At span	At column	At span	At column	At span	At column	At span
MEd	-377.1	294.7	-159.7	195.1	-266.1	190.6	-110.6	124.3
MRd	-334.7	325.1	-175.6	214.3	-335.8	320	-216.8	301.6
Utilization	113 %	91 %	91 %	91 %	79 %	60 %	51 %	41 %

Tendon layout F

$N_{x.cstrip} := 0$ — Number of tendons in interior strip x-direction, column strip

$N_{x.mstrip} := 0$ — Number of tendons in interior strip x-direction, middle strip

$N_{y.cstrip} := 0$ — Number of tendons in interior strip y-direction, column strip

$N_{y.mstrip} := 0$ — Number of tendons in interior strip y-direction, middle strip

$$q_{p.x.cstrip} := \frac{N_{x.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^{\ 2}} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, column strip

$$q_{p.x.mstrip} := \frac{N_{x.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_x^{\ 2}} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, x-direction, middle strip

$$q_{p.y.cstrip} := \frac{N_{y.cstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^{\ 2}} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, column strip

$$q_{p.y.mstrip} := \frac{N_{y.mstrip} \cdot P_{mt} \cdot 8 \cdot h}{span_y^{\ 2}} = 0 \cdot \frac{kN}{m}$$

Equivalent upward force from tendons, y-direction, middle strip

$M_{p.column.x.cstrip} := 0.1 \cdot q_{p.x.cstrip} \cdot span_x^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment at column, x-direction, column strip

$M_{p.span.x.cstrip} := -0.08 \cdot q_{p.x.cstrip} \cdot span_x^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment in span, x-direction, column strip

$M_{p.column.x.mstrip} := 0.1 \cdot q_{p.x.mstrip} \cdot span_x^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment at column, x-direction, middle strip

$M_{p.span.x.mstrip} := -0.08 \cdot q_{p.x.mstrip} \cdot span_x^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment in span, x-direction, middle strip

$M_{p.column.y.cstrip} := 0.125 \cdot q_{p.y.cstrip} \cdot span_y^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment at column, y-direction, column strip

$M_{p.span.y.cstrip} := -0.0703 \cdot q_{p.y.cstrip} \cdot span_y^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment in span, y-direction, column strip

$M_{p.column.y.mstrip} := 0.125 \cdot q_{p.y.mstrip} \cdot span_y^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment at column, y-direction, middle strip

$M_{p.span.y.mstrip} := -0.0703 \cdot q_{p.y.mstrip} \cdot span_y^{\,2} = 0 \cdot kN \cdot m$ Prestressing moment in span, y-direction, middle strip

$M_{0.column.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, x-direction, column strip

$M_{0.span.x.cstrip} := N_{x.cstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, x-direction, column strip

$M_{0.column.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, x-direction, middle strip

$M_{0.span.x.mstrip} := N_{x.mstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, x-direction, middle strip

$M_{0.column.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, y-direction, column strip

$M_{0.span.y.cstrip} := N_{y.cstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, y-direction, column strip

$M_{0.column.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot e_{top} = 0 \cdot kN \cdot m$ Primary moment at column, y-direction, middle strip

$M_{0.span.y.mstrip} := N_{y.mstrip} \cdot P_{mt} \cdot -e_{bottom} = 0 \cdot kN \cdot m$ Primary moment in span, y-direction, middle strip

Characteristic hyperstatic moments:

$M_{Ek.h.column.x.cstrip} := M_{p.column.x.cstrip} - M_{0.column.x.cstrip} = 0 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.span.x.cstrip} := M_{p.span.x.cstrip} - M_{0.span.x.cstrip} = 0 \cdot kN \cdot m$ x-direction, column strip

$M_{Ek.h.column.x.mstrip} := M_{p.column.x.mstrip} - M_{0.column.x.mstrip} = 0 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.span.x.mstrip} := M_{p.span.x.mstrip} - M_{0.span.x.mstrip} = 0 \cdot kN \cdot m$ x-direction, middle strip

$M_{Ek.h.column.y.cstrip} := M_{p.column.y.cstrip} - M_{0.column.y.cstrip} = 0 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.span.y.cstrip} := M_{p.span.y.cstrip} - M_{0.span.y.cstrip} = 0 \cdot kN \cdot m$ y-direction, column strip

$M_{Ek.h.column.y.mstrip} := M_{p.column.y.mstrip} - M_{0.column.y.mstrip} = 0 \cdot kN \cdot m$ y-direction, middle strip

$M_{Ek.h.span.y.mstrip} := M_{p.span.y.mstrip} - M_{0.span.y.mstrip} = 0 \cdot kN \cdot m$ y-direction, middle strip

Design moments:

$$M_{Ed.column.x.cstrip} := \gamma_g \cdot M_{Ek.g.column.x.cstrip} + \gamma_q \cdot M_{Ek.q.column.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.cstrip} = -403.65 \cdot kN \cdot m$$

$$M_{Ed.span.x.cstrip} := \gamma_g \cdot M_{Ek.g.span.x.cstrip} + \gamma_q \cdot M_{Ek.q.span.x.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.cstrip} = 286.5 \cdot kN \cdot m$$

$$M_{Ed.column.x.mstrip} := \gamma_g \cdot M_{Ek.g.column.x.mstrip} + \gamma_q \cdot M_{Ek.q.column.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.x.mstrip} = -172.99 \cdot kN \cdot m$$

$$M_{Ed.span.x.mstrip} := \gamma_g \cdot M_{Ek.g.span.x.mstrip} + \gamma_q \cdot M_{Ek.q.span.x.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.x.mstrip} = 191 \cdot kN \cdot m$$

$$M_{Ed.column.y.cstrip} := \gamma_g \cdot M_{Ek.g.column.y.cstrip} + \gamma_q \cdot M_{Ek.q.column.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.cstrip} = -314.69 \cdot kN \cdot m$$

$$M_{Ed.span.y.cstrip} := \gamma_g \cdot M_{Ek.g.span.y.cstrip} + \gamma_q \cdot M_{Ek.q.span.y.cstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.cstrip} = 173.92 \cdot kN \cdot m$$

$$M_{Ed.column.y.mstrip} := \gamma_g \cdot M_{Ek.g.column.y.mstrip} + \gamma_q \cdot M_{Ek.q.column.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.column.y.mstrip} = -134.87 \cdot kN \cdot m$$

$$M_{Ed.span.y.mstrip} := \gamma_g \cdot M_{Ek.g.span.y.mstrip} + \gamma_q \cdot M_{Ek.q.span.y.mstrip} \cdots + \gamma_p \cdot M_{Ek.h.span.y.mstrip} = 115.94 \cdot kN \cdot m$$

$$S_{p.x.cstrip} := N_{x.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$$

Forces in tendons, x-direction, column strip

$$S_{p.x.mstrip} := N_{x.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$$

Forces in tendons, x-direction, middle strip

$$S_{p.y.cstrip} := N_{y.cstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$$

Forces in tendons, y-direction, column strip

$$S_{p.y.mstrip} := N_{y.mstrip} \cdot \left(P_{mt} + \Delta\sigma_{p.ULS} \cdot A_p\right) = 0 \cdot kN$$

Forces in tendons, y-direction, middle strip

Effective slab thicknesses:

$$d_{eff.column.x.cstrip} := \frac{d_{p.column} \cdot S_{p.x.cstrip} + d_{d.column.x} \cdot S_{d.top.x.cstrip}}{S_{p.x.cstrip} + S_{d.top.x.cstrip}} = 187 \cdot mm$$

$$d_{eff.span.x.cstrip} := \frac{d_{p.span} \cdot S_{p.x.cstrip} + d_{d.span.x} \cdot S_{d.btm.x.cstrip}}{S_{p.x.cstrip} + S_{d.btm.x.cstrip}} = 190 \cdot mm$$

$$d_{eff.column.x.mstrip} := \frac{d_{p.column} \cdot S_{p.x.mstrip} + d_{d.column.x} \cdot S_{d.top.x.mstrip}}{S_{p.x.mstrip} + S_{d.top.x.mstrip}} = 187 \cdot mm$$

$$d_{eff.span.x.mstrip} := \frac{d_{p.span} \cdot S_{p.x.mstrip} + d_{d.span.x} \cdot S_{d.btm.x.mstrip}}{S_{p.x.mstrip} + S_{d.btm.x.mstrip}} = 190 \cdot mm$$

$$d_{eff.column.y.cstrip} := \frac{d_{p.column} \cdot S_{p.y.cstrip} + d_{d.column.y} \cdot S_{d.top.y.cstrip}}{S_{p.y.cstrip} + S_{d.top.y.cstrip}} = 171 \cdot mm$$

$$d_{eff.span.y.cstrip} := \frac{d_{p.span} \cdot S_{p.y.cstrip} + d_{d.span.y} \cdot S_{d.btm.y.cstrip}}{S_{p.y.cstrip} + S_{d.btm.y.cstrip}} = 180 \cdot mm$$

$$d_{eff.column.y.mstrip} := \frac{d_{p.column} \cdot S_{p.y.mstrip} + d_{d.column.y} \cdot S_{d.top.y.mstrip}}{S_{p.y.mstrip} + S_{d.top.y.mstrip}} = 171 \cdot mm$$

$$d_{eff.span.y.mstrip} := \frac{d_{p.span} \cdot S_{p.y.mstrip} + d_{d.span.y} \cdot S_{d.btm.y.mstrip}}{S_{p.y.mstrip} + S_{d.btm.y.mstrip}} = 180 \cdot mm$$

α-factors:

$$\alpha_{column.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.top.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.cstrip}} = 0.06$$

$$\alpha_{span.x.cstrip} := \frac{S_{p.x.cstrip} + S_{d.btm.x.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.cstrip}} = 0.04$$

$$\alpha_{column.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.top.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.x.mstrip}} = 0.03$$

$$\alpha_{span.x.mstrip} := \frac{S_{p.x.mstrip} + S_{d.btm.x.mstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.x.mstrip}} = 0.04$$

$$\alpha_{column.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.top.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.column.y.cstrip}} = 0.08$$

$$\alpha_{span.y.cstrip} := \frac{S_{p.y.cstrip} + S_{d.btm.y.cstrip}}{0.8 \cdot f_{cd} \cdot 3m \cdot d_{eff.span.y.cstrip}} = 0.05$$

$$\alpha_{column.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.top.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.column.y.mstrip}} = 0.03$$

$$\alpha_{span.y.mstrip} := \frac{S_{p.y.mstrip} + S_{d.btm.y.mstrip}}{0.8 \cdot f_{cd} \cdot 6m \cdot d_{eff.span.y.mstrip}} = 0.05$$

Moment capacities:

$$M_{Rd.column.x.cstrip} := -0.8 \cdot \alpha_{column.x.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.x.cstrip}\right) \cdot 3m \cdot d_{eff.column.x.cstrip}{}^{2} \cdot f_{cd} = -127.59 \cdot$$

$$M_{Rd.span.x.cstrip} := 0.8 \cdot \alpha_{span.x.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.x.cstrip}\right) \cdot 3m \cdot d_{eff.span.x.cstrip}{}^{2} \cdot f_{cd} = 95.61 \cdot kN \cdot m$$

$$M_{Rd.column.x.mstrip} := -0.8 \cdot \alpha_{column.x.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.x.mstrip}\right) \cdot 3m \cdot d_{eff.column.x.mstrip}{}^{2} \cdot f_{cd} = -64.5$$

$$M_{Rd.span.x.mstrip} := 0.8 \cdot \alpha_{span.x.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.x.mstrip}\right) \cdot 3m \cdot d_{eff.span.x.mstrip}{}^{2} \cdot f_{cd} = 95.61 \cdot kN \cdot m$$

$$M_{Rd.column.y.cstrip} := -0.8 \cdot \alpha_{column.y.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.y.cstrip}\right) \cdot 3m \cdot d_{eff.column.y.cstrip}{}^{2} \cdot f_{cd} = -130.5 \cdot k$$

$$M_{Rd.span.y.cstrip} := 0.8 \cdot \alpha_{span.y.cstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.y.cstrip}\right) \cdot 3m \cdot d_{eff.span.y.cstrip}{}^{2} \cdot f_{cd} = 90.49 \cdot kN \cdot m$$

$$M_{Rd.column.y.mstrip} := -0.8 \cdot \alpha_{column.y.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{column.y.mstrip}\right) \cdot 6m \cdot d_{eff.column.y.mstrip}{}^{2} \cdot f_{cd} = -103.4$$

$$M_{Rd.span.y.mstrip} := 0.8 \cdot \alpha_{span.y.mstrip} \cdot \left(1 - 0.4 \cdot \alpha_{span.y.mstrip}\right) \cdot 6m \cdot d_{eff.span.y.mstrip}{}^{2} \cdot f_{cd} = 180.98 \cdot kN \cdot m$$

	X-direction				Y-direction			
	Column strip		Middle strip		Column strip		Middle strip	
	At column	At span	At column	At span	At column	At span	At column	At span
MEd	-403.7	286.5	-173	191	-314.7	173.9	-134.9	115.9
MRd	-127.6	95.6	-64.6	95.6	-130.5	90.5	-103.4	181
Utilization	316 %	300 %	268 %	200 %	241 %	192 %	130 %	64 %