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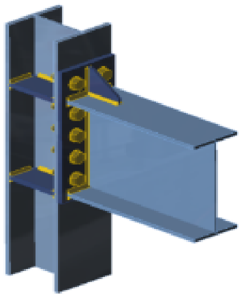
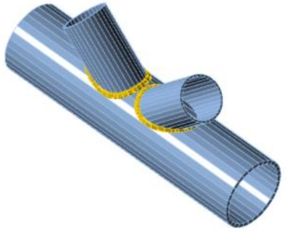
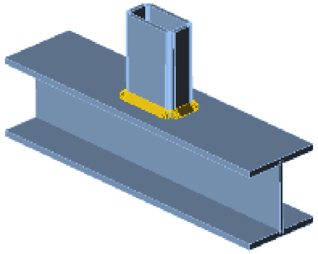
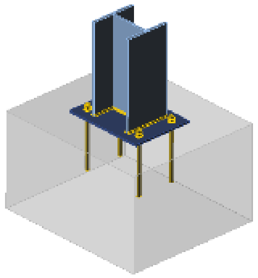
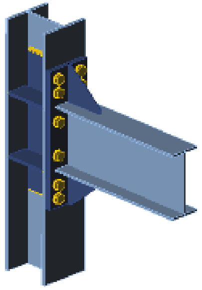
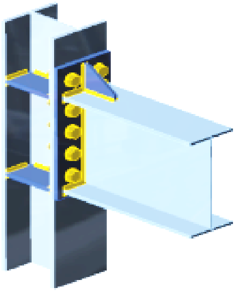
Connection design
by Component Based Finite Element Method

Lecture 4
Column base

List of lectures

1) Beam to column moment connection
2) Hollow section joints
3) Joint of hollow to open section
4) **Column base**
5) Seismically qualified joints
6) Joints at elevated temperature

Aims and objectives

- Provide information on the behavior of the column base
- Introduce the principles of the Component Method (CM) for column base design
- Introduce the principles of Component Based Finite Element Method (CBFEM) for the column base
- Provide an online training to students and engineers
- Illustrate the differences between numerical simulation and numerical calculation, e.g., between research-oriented and design-oriented FEM.
- Show the process of Validation & Verification
- Offer a list of references relevant to the topic

Lecture 4

Column base

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Tutorial

- This lecture describes the principles of Finite Element Method of column base by applying Component Based FEM (CBFEM).
- The behavior of the base plate subjected to compression and bending is shown on the analytical design by the component method.
- Validation, verification and benchmark cases using Component Based Finite Element Method are presented.

- Material was prepared under the R&D project MERLION II supported by Technology Agency of the Czech Republic, project No TH02020301.

Outline of the lecture

- **Introduction**
  - Anchor bolts
  - Classification
  - Assessment I
- **Component method**
  - Component in compression
  - Component in tension
  - Assembly of components
  - Assessment II
- **Component Based Finite Eelement Method**
  - Validation
  - Verification
  - Sensitivity study
  - Benchmark case
  - Assessment III
- **Summary**

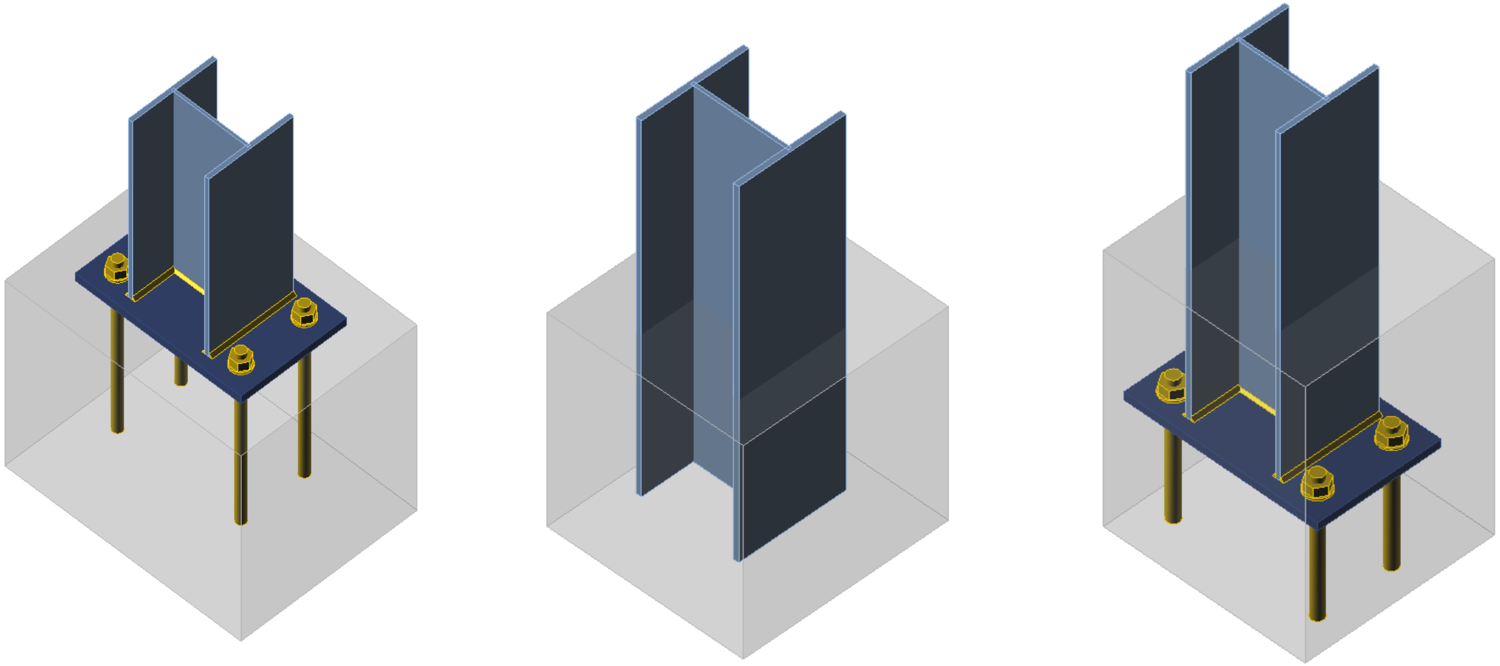
Introduction

Lecture 4

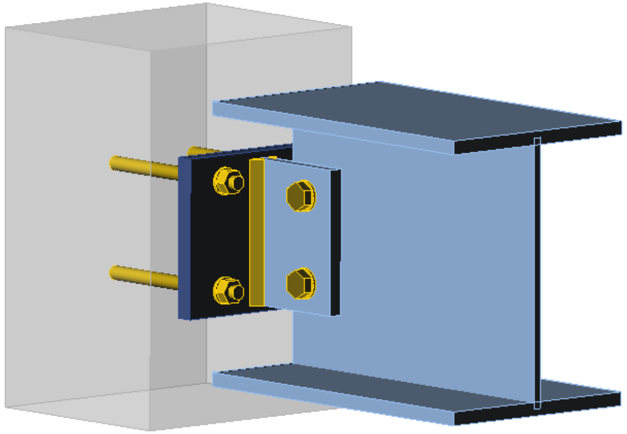
Column base

Introduction

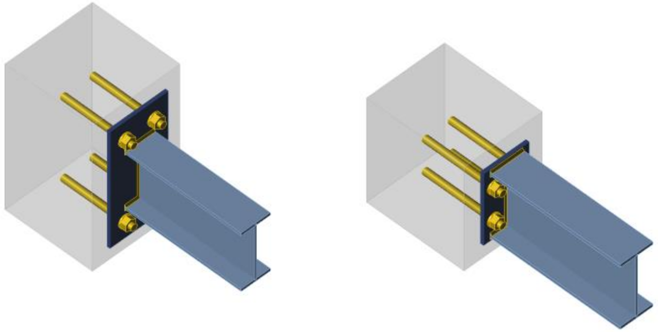
- Steel structures are fixing to concrete foundation/structure by base plate/end plates, embedding and its combination.
- The aim of this lecture are joints with base plate fixed to concrete structure by anchor bolts.



Introduction

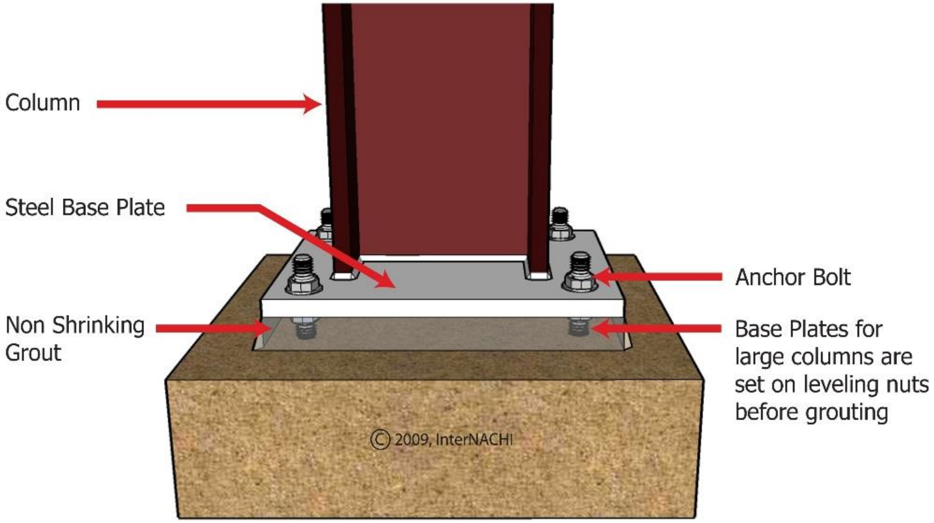


- The same principles are used for end plate fixed to concrete structure by anchor bolts.



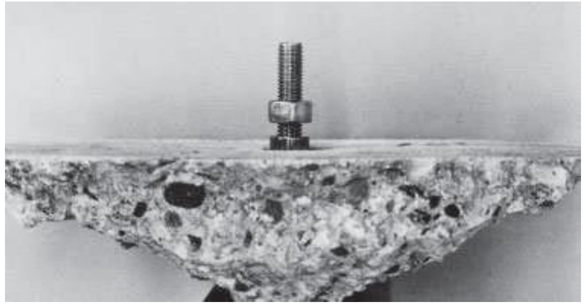
- The base plate is usually positioned on the concrete block by pickings or levelling nuts and fixed by grout. The erection has no substantial influence to design resistance.

  If the anchor bolts are designed not embedded (during erection or use) it takes into account in design.

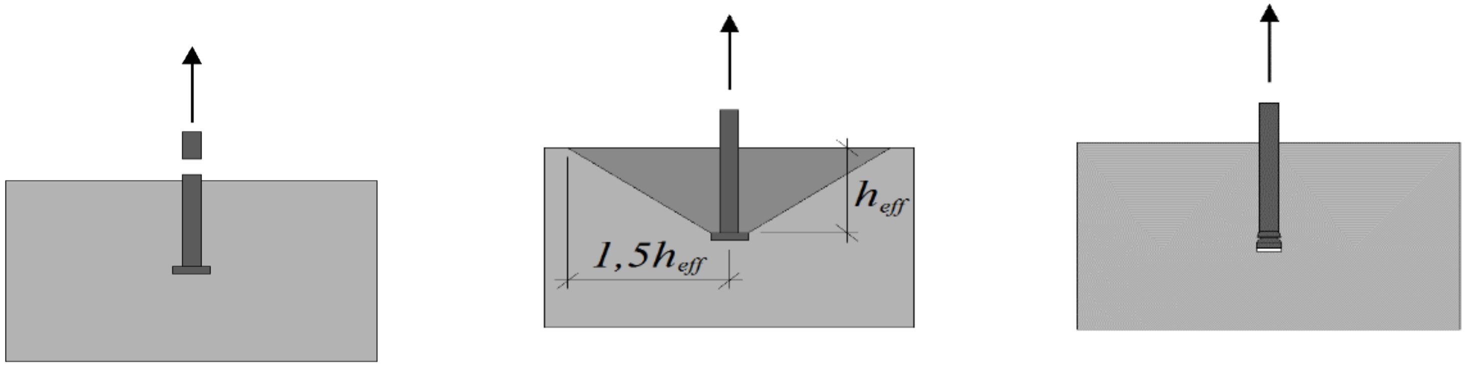


Design resistance of anchor bolt in tension

Anchor bolts are designed for its resistance in tension according to EN1992-4:2018 for all possible failure modes.



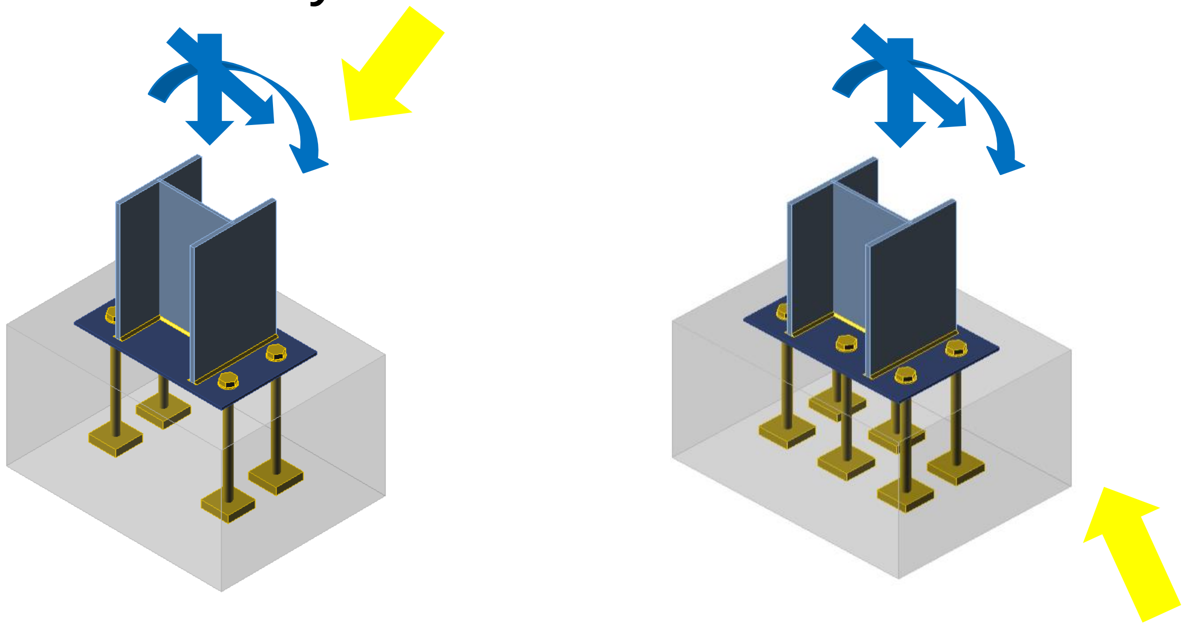
- Basic failure modes in tension are:
  - Steel failure of fastener
  - Concrete cone failure
  - Pull-out failure of fastener



Note: In structural steel column bases is asked the ductile steel fastener´s failure mode, if structurally possible, compared to anchoring of secondary structures.

Distribution of forces between anchor bolts in tension

- EN1992-4:2018 expects, that forces between anchor bolts are distributed elastically. It meets the column base with one anchor bolt row.



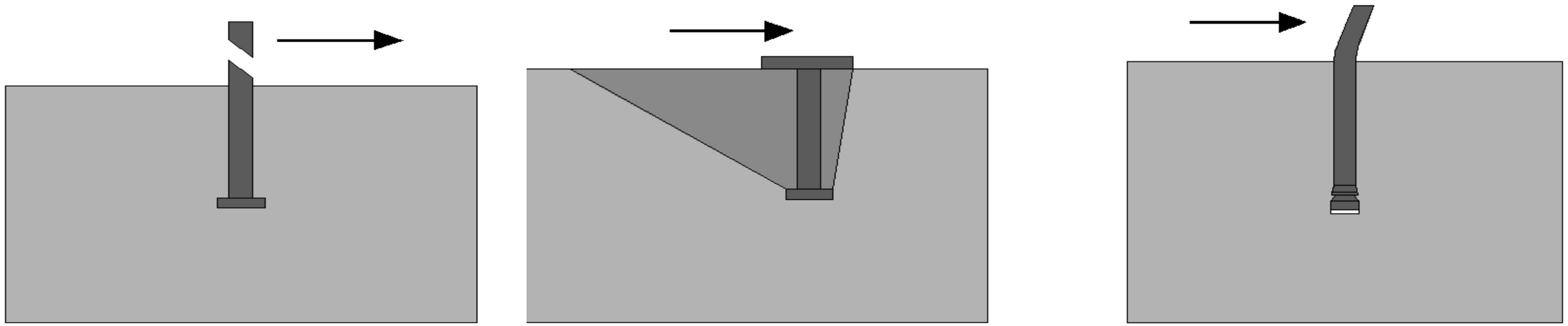
- Plastic analyses according to CEN/TR 17081:2018 is used for distribution of bolt forces for more anchor bolt rows in tension. In this case is asked to be the govern failure ductile, e.g. the steel failure of fastener. The developed prying forces are taken into account .

Design resistance of anchor bolt in shear

Anchor bolts for resistance in shear are designed according to EN1992-4:2018 for all possible failure modes.

Basic failure modes in shear are:

- Steel failure of fastener
- Concrete edge failure/Pry-out failure
- Pull-out failure of fastener



Column base classification

To simplify global analyses are classified joints in Ch. 5

of EN1993-1-8:2006 based on

- Best engineering practice
- Actual influence of particular joint to current frame design, which implicates recalculation.
- Simplified assumption of frame behaviour

According to initial joint bending stiffness are column bases classified

- Similar to beam-to-column joints
- Related to the column bending stiffness

Column base classification by bending stiffness

Limit between rigid and semi-rigid column bases based on simplified assumption of frame behaviour.

- **For non-sway frames** is derived from column resistance

for $\bar{\lambda}_o \le 0,5$ $\qquad S_{j,ini} \ge 0$

for $0,5 < \bar{\lambda}_o < 3,93$ $\qquad S_{j,ini} \ge 7\,(2\bar{\lambda}_o - 1)\,E\,I_c\,/\,L_c$

and for $\bar{\lambda}_o \ge 3,93$ $\qquad S_{j,ini} \ge 48\,E\,I_c\,/\,L_c$

where $\bar{\lambda}_o$ is relative slenderness for simple supported column at both ends.

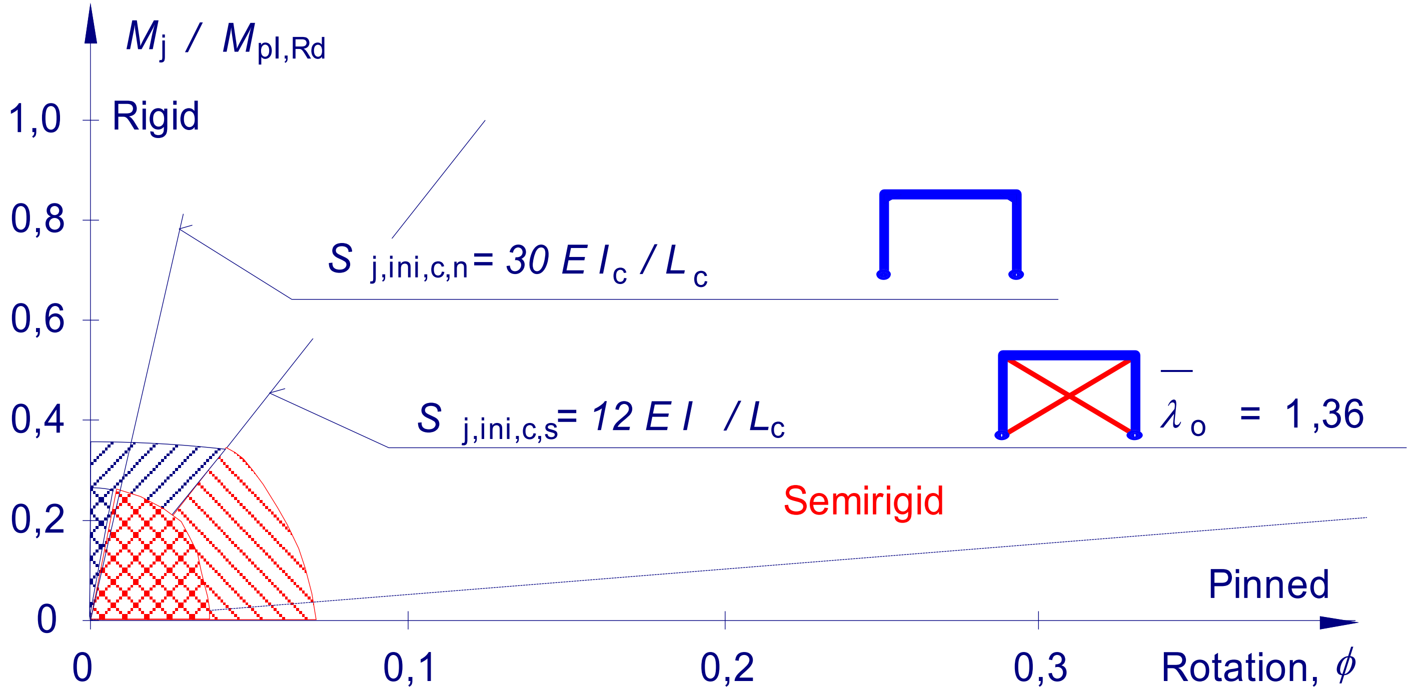
Is valid for limited stiffness $12\,E\,I_c\,/\,L_c$

- **For sway frames** is derived from limiting sway $S_{j,ini} \ge 30\,E\,I_c\,/\,L_c$

The limit between pinned and semi-rigid is expected 0,5.

Column base classification by bending stiffness

Below are shown the limits between rigid, semi-rigid column and pinned column bases based on simplified assumption of frame behaviour.

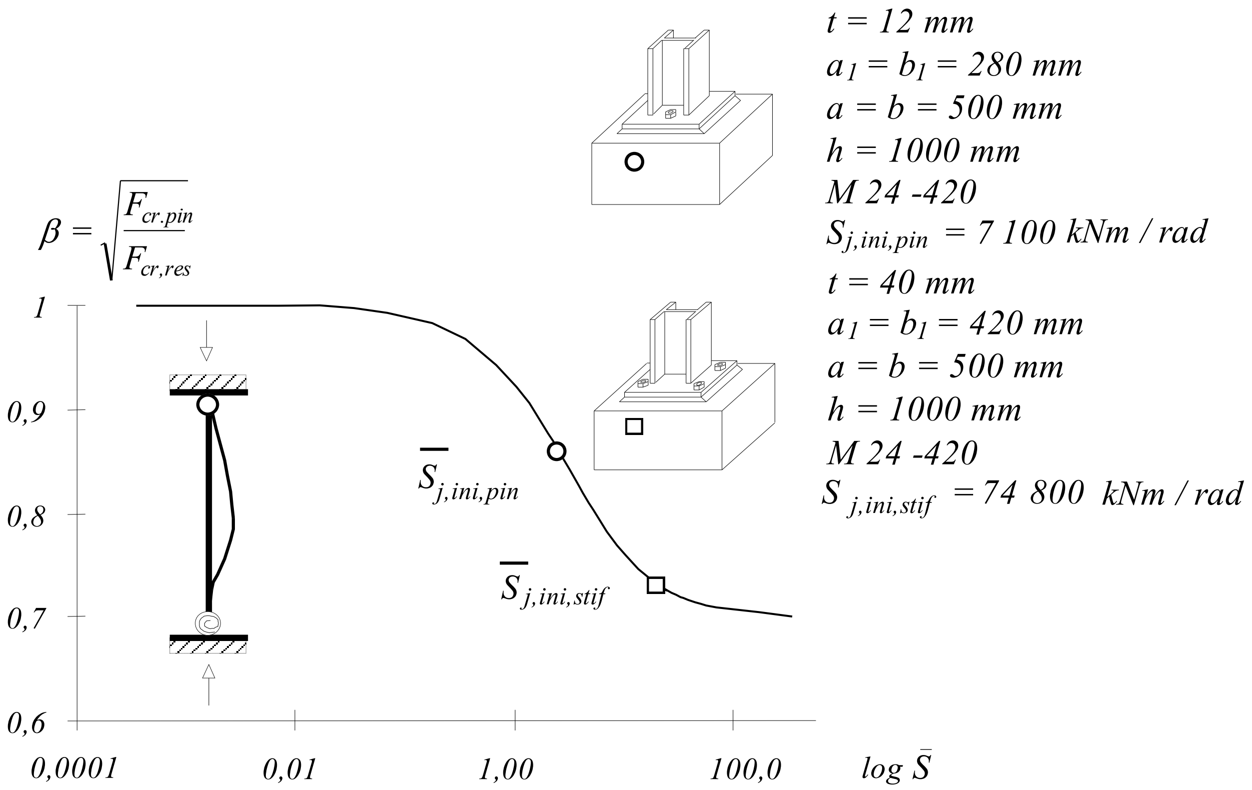


The limits assure accuracy in design of frame 5% for resistance and 20% for serviceability.

Classification of column base in non-sway frame

Below is shown the influence of bending stiffness of two column bases to the column buckling length on example of column HEB200.

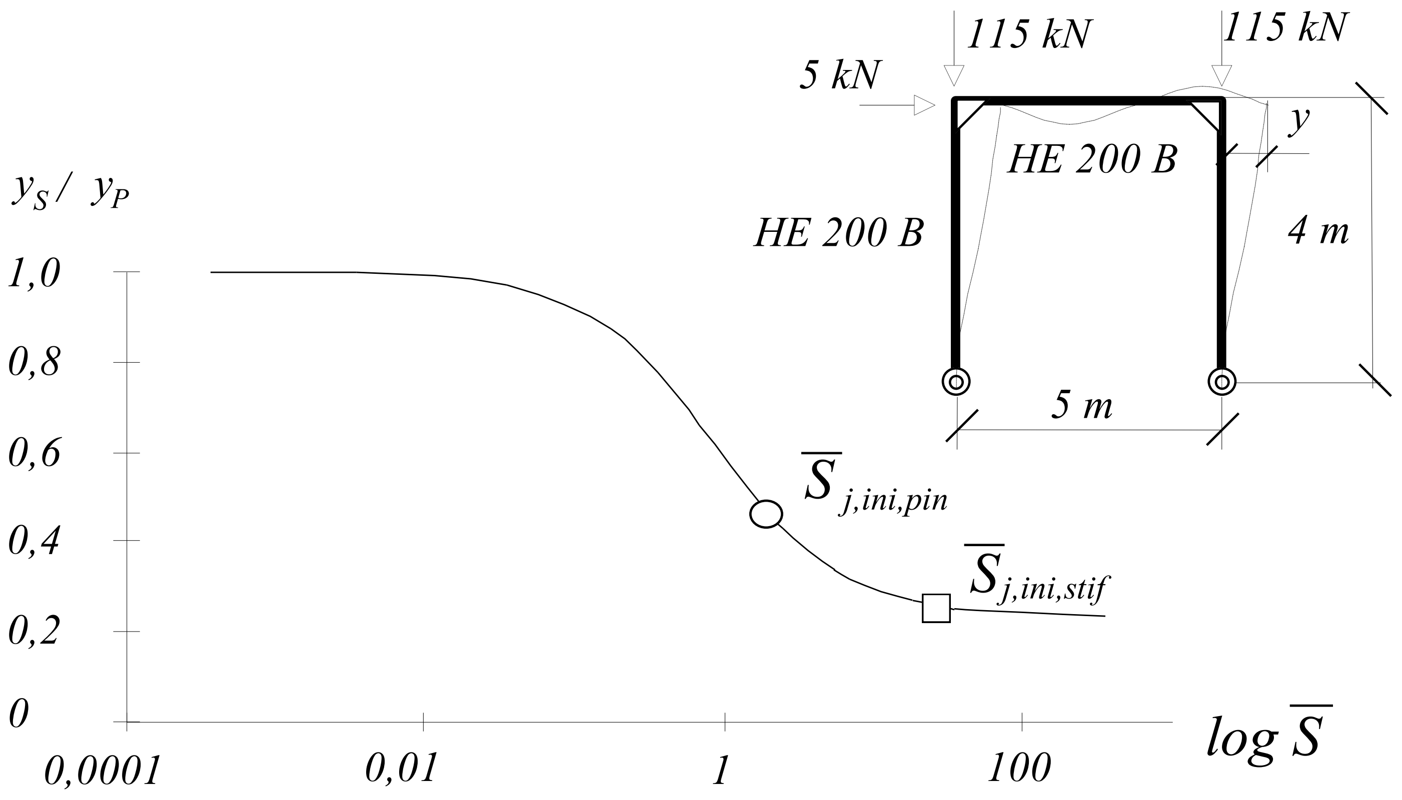
On the vertical axes is parameter of buckling length β; β = 0,7 for rigid column base and β = 1,0 for pin one. On the horizontal axes is the relative slenderness of base plate to column in logarithmic scale. The points represent influence of the real column bases on buckling length.



Classification of column base in sway frame

Below is shown the influence of bending stiffness of column bases in sway portal frame.

On the vertical axes is parameter of sway y_s/y_p; y_s/y_p = 0,33 for rigid column base and y_s/y_p = 1,0 for pin one. On the horizontal axes is the relative slenderness of base plate to column in logarithmic scale. The points represent influence of the real column bases on buckling length of columns.



Assessment I

- What are the basic failure modes of anchor bolts in tension?
- What should be the failure mode of anchor bolt in case of plastic distribution of forces in column base with more bolt rows?
- What are the basic failure modes of anchor bolts in shear?
- What is the reason of classification of joints by bending stiffness?
- What principles are used for classification of joints by bending stiffness?
- For what accuracy was derived the limit between rigid and semi-rigid column bases for simplified assumption of frame behaviour?

Component method

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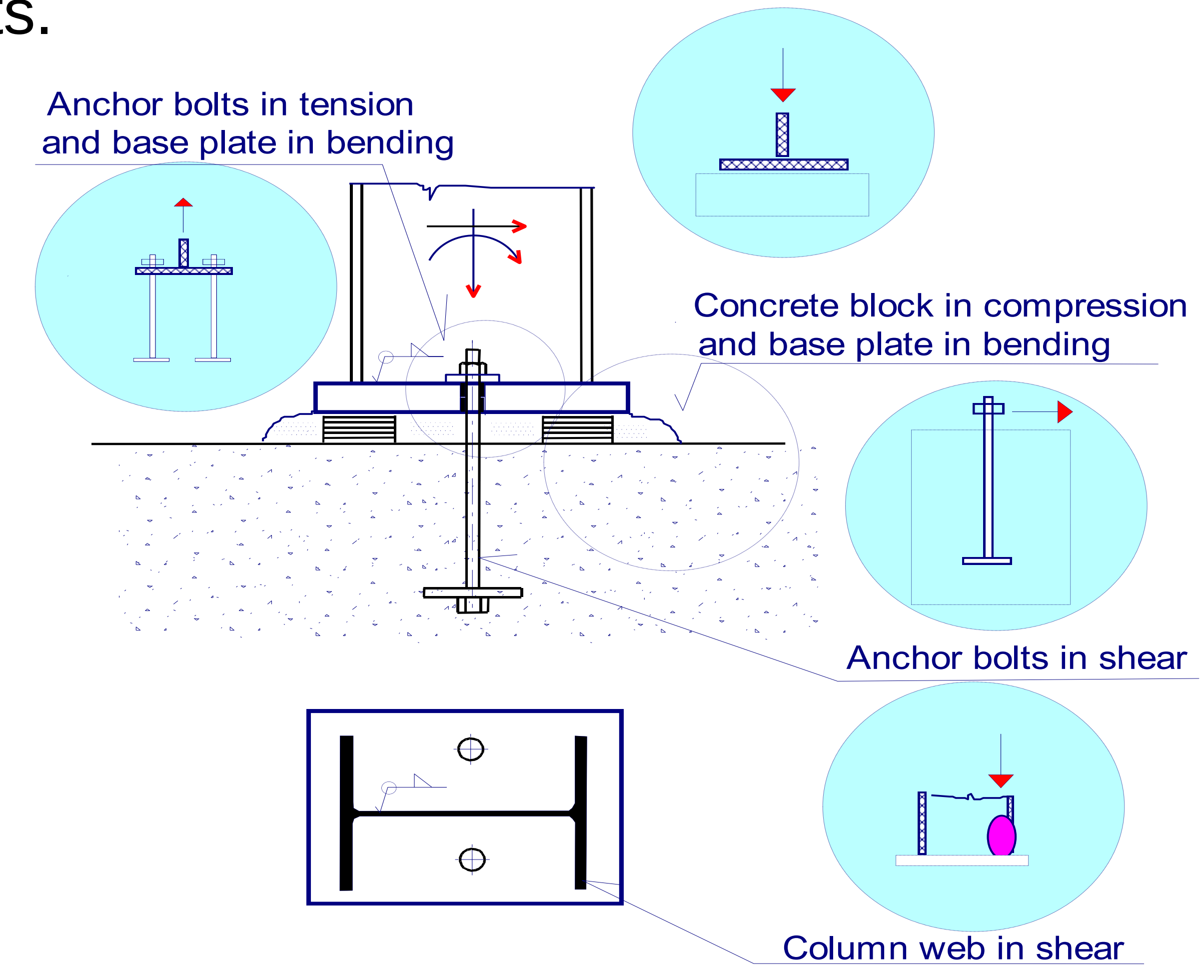
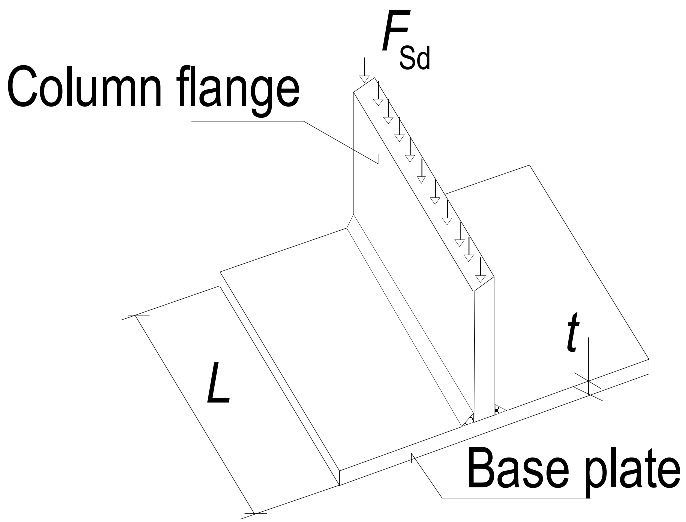
Component method for column bases

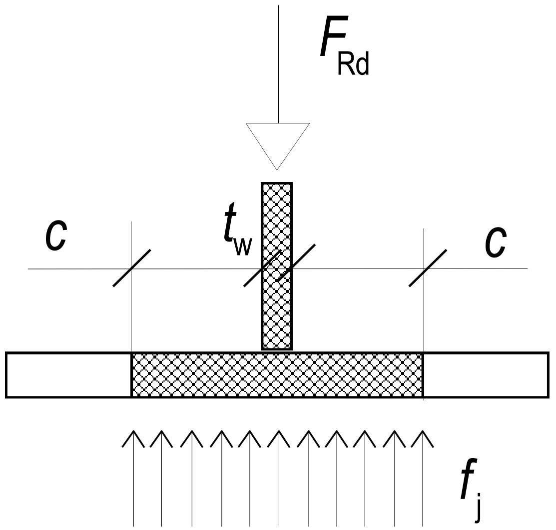
- In the first step of component method is the joint divided into components.



Component base plate in bending and concrete block in compression

- **Base plate is flexible under rigid flange/web plates** and is taken into account in design by
    - Effective rigid area under the flexible plate A_{eff}.
- **Concrete block occurs in spatial stress** and is taken into account in design by
    - Concrete design strength in joint f_{jd}.





Concrete design strength in joint f_{jd}

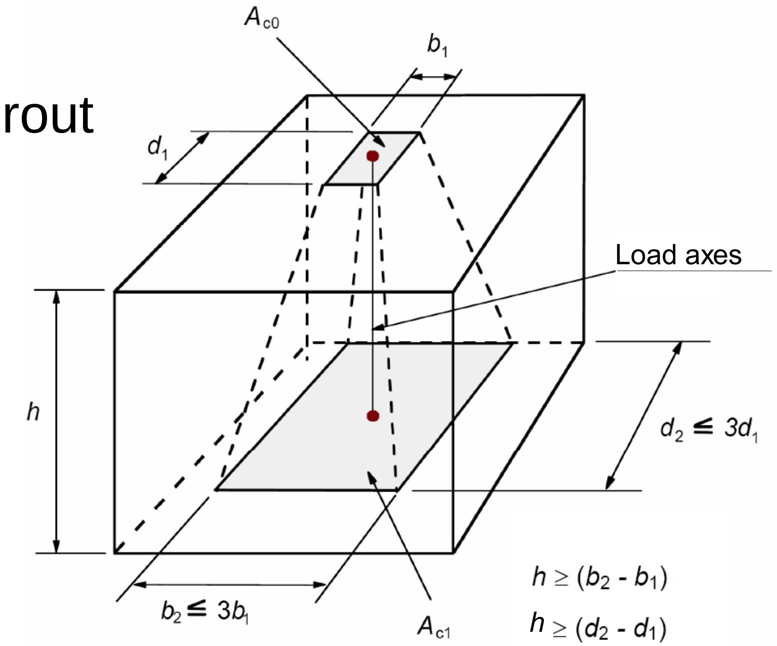
- Concrete design strength in joint f_{jd} is derived from the concrete resistance to concentrated force $F_{Rd,u}$.

$$f_{jd} = \frac{\beta_j \ F_{Rdu}}{b_{ef} \ l_{ef}} = \frac{\beta_j \ A_{c0} \ f_{cd} \sqrt{\dfrac{A_{c1}}{A_{c0}}}}{A_{c0}} = \beta_j \ f_{cd} \sqrt{\frac{A_{c1}}{A_{c0}}} \leq \frac{3{,}0 \ A_{c0} \ f_{cd}}{A_{c0}} = 3{,}0 \, f_{cd}$$

where

β_j is joint coefficient due to lower quality of grout compared to concrete and is taken 2/3

f_{cd} is concrete compressive strength



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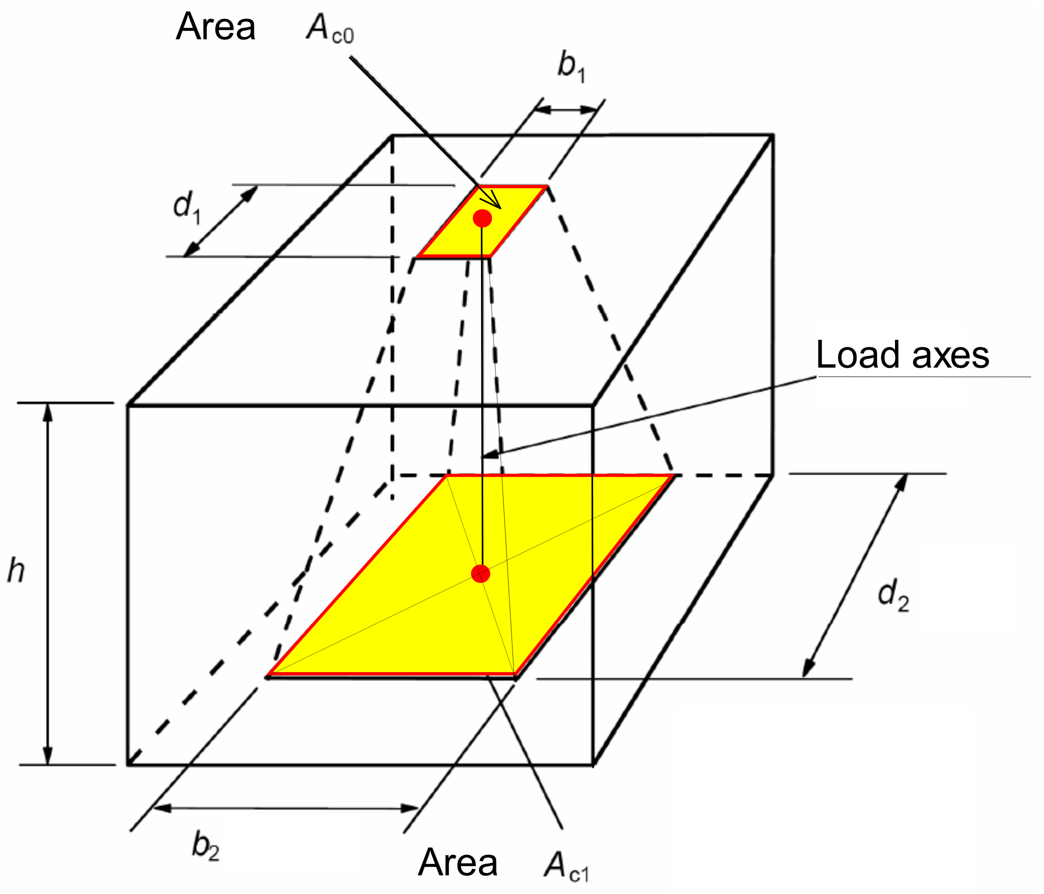
Concrete resistance to concentrated force $F_{Rd,u}$

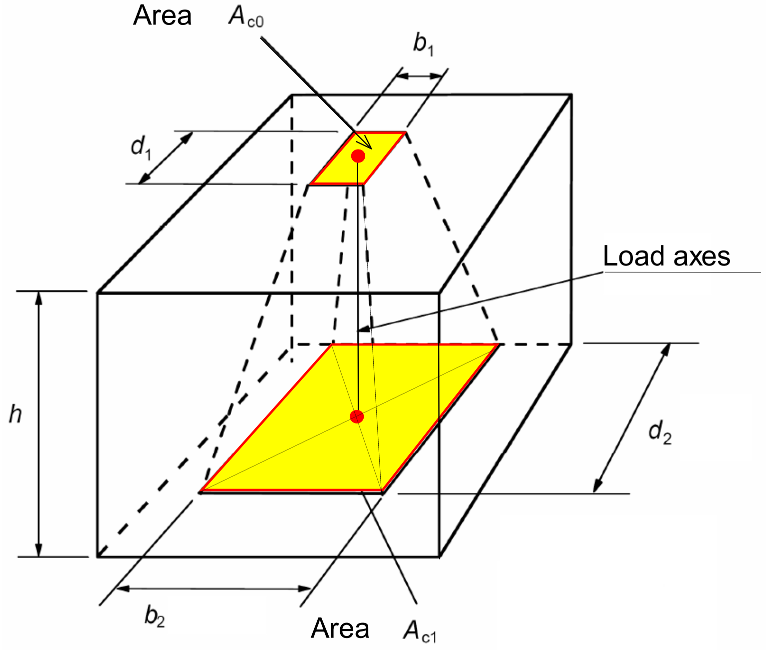
- Concrete resistance to concentrated force $F_{Rd,u}$ is taken as homogenous force $F_{Rd,u}$ on the loaded area A_{c0}. It is limited by geometry of concrete block.

Note:
In spatial stress is failure mode
crushing of concrete under the base plate.



Concrete resistance to concentrated force $F_{Rd,u}$

- Concrete resistance to the concentrated force $F_{Rd,u}$ is calculated from the geometry of the concrete block as



$$F_{Rd,u} = A_{c0}\, f_{cd} \sqrt{\frac{A_{c1}}{A_{c0}}} \le 3{,}0\, A_{c0}\, f_{cd}$$

$$A_{c0} = b_1\, d_1$$

$$A_{c1} = b_2\, d_2$$

$$h \ge b_2 - b_1;\ h \ge d_2 - d_1$$

$$3 \cdot b_1 \ge b_2 \text{ and } 3 \cdot d_1 \ge d_2$$

where

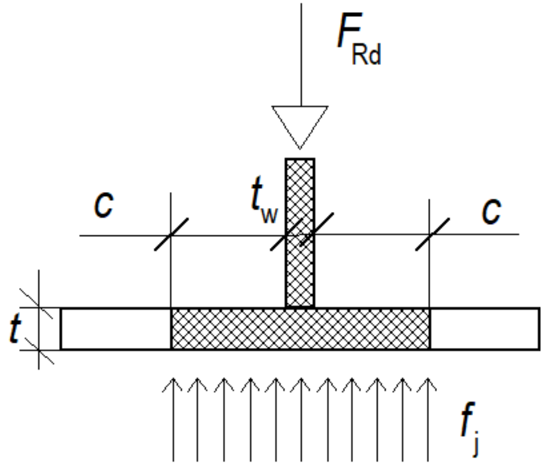
f_{cd} is concrete the compressive strength

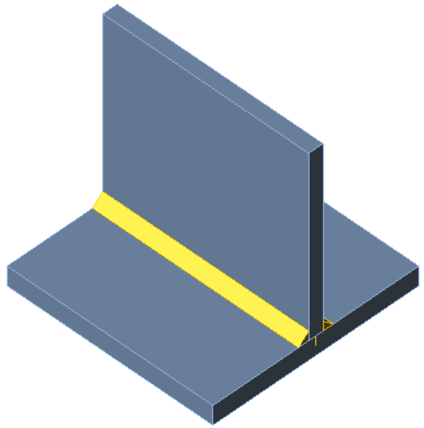
A_{c0} is the area of crushing of the concrete Cl. 6.7(2) in EN 1992-1-1

Effective flexible plate on the concrete block

- Effective flexible plate on the concrete block, where is reached the concrete design strength in joint f_{jd}, **is limited by elastic deformation of the base plate**. From this assumption is calculated effective width *c* round the column´s flanges/webs as

$$c = t\sqrt{\frac{f_y}{3\, f_{jd}\, \gamma_{M0}}}$$





where

t is the plate thickness

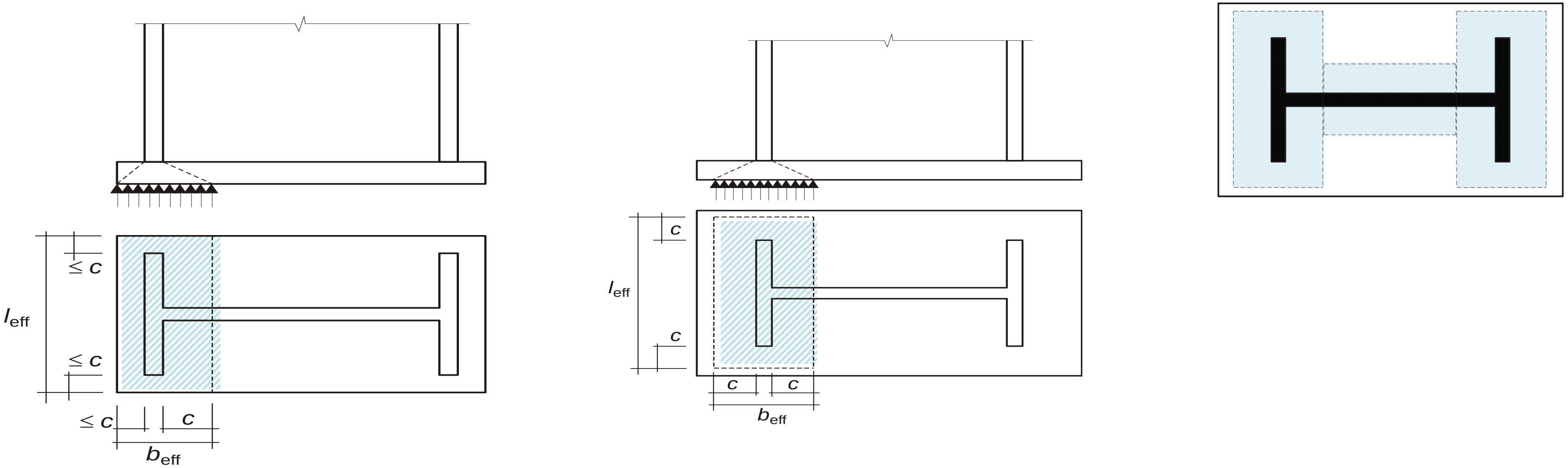
f_y is the base plate yield strength

f_{jd} is the design bearing strength of the joint

γ_{M0} is the partial safety factor for concrete

Effective area under the base plate

- The effective area of design contact under the base plate is created around the column´s web and flanges by the T-stub effective width *c*



- Into account is taken only real the projection of the physical length of the basic joint component represented by the T-stub.

Stiffness of component concrete in compression and base plate in bending

- Stiffness coefficient of concrete in compression under base plate is taken as deformation of elastic hemisphere

$$k_c = \frac{F}{\delta\, E} = \frac{E_c\,\sqrt{a_{eq,el}\,L}}{1{,}5 \cdot 0{,}85\, E} = \frac{E_c\,\sqrt{a_{eq,el}\,L}}{1{,}275\, E}$$

where $a_{eq,el}$ is effective width of T-stub
L is the flange/web length

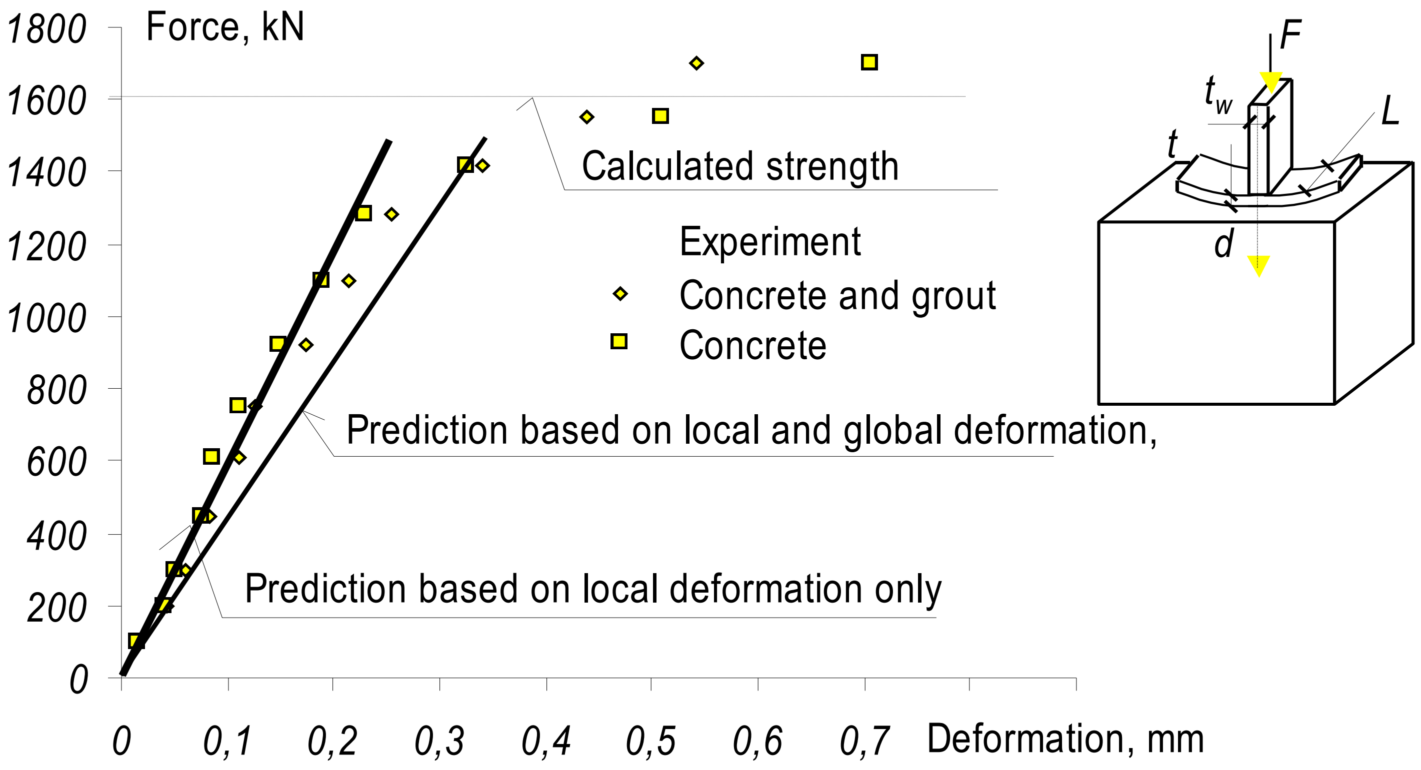
- Effective T-stub width $a_{eq,el}$ in elastic stage may be assumed as

$$a_{eq,el} = t_w + 2{,}5\, t \approx a_{eq,st} =$$

$$= t_w + 2\, c = t_w + 2\, t \sqrt{\frac{f_y}{3\, f_{jd}\, \gamma_{M0}}}$$

Comparison to experiments

- On the graph is compared the prediction of stiffness of component concrete in compression and base plate in bending.
- On the vertical axes is the applied force and on horizontal axes the deformation.

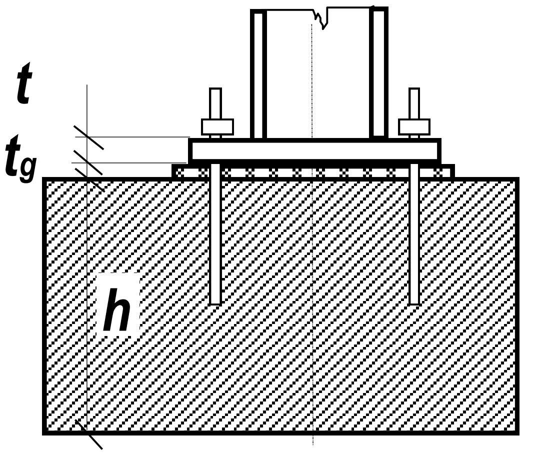


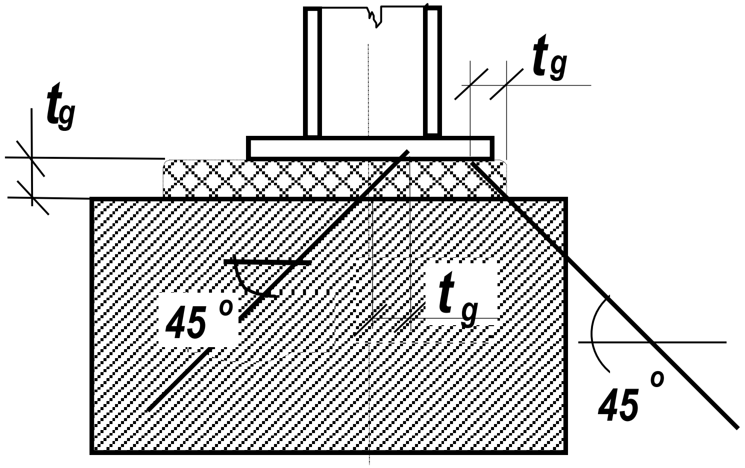
Influence of grout to column base resistance

- Grout with higher strength than concrete block may be taken into account to improve resistance.
- Grout with lower strength than concrete block behaves under base plate as liquid and is taken into account by joint reduction factor β_j.

$$\beta_j = 2 / 3$$

$$f_{c.g} \geq 0{,}2\, f_c$$
$$t_g \leq 0{,}2 \min\ (a\ ;\ b)$$
$$t_g \geq 0{,}2 \min\ (a\ ;\ b)$$





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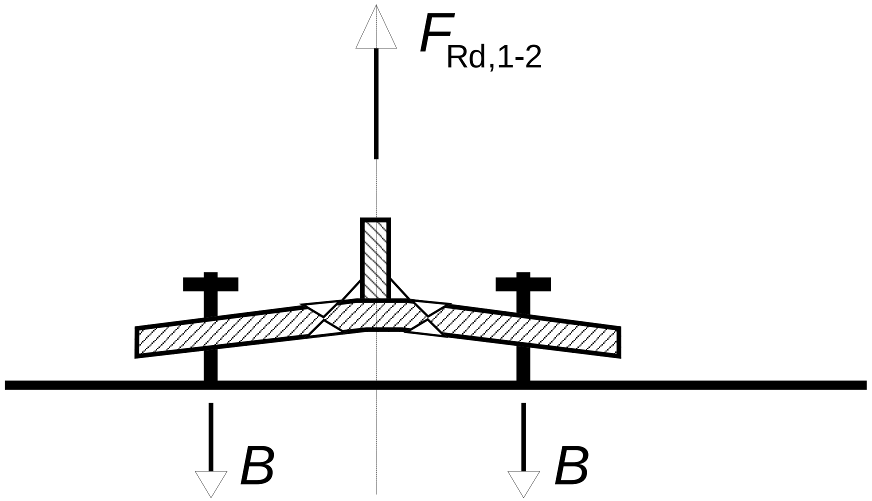
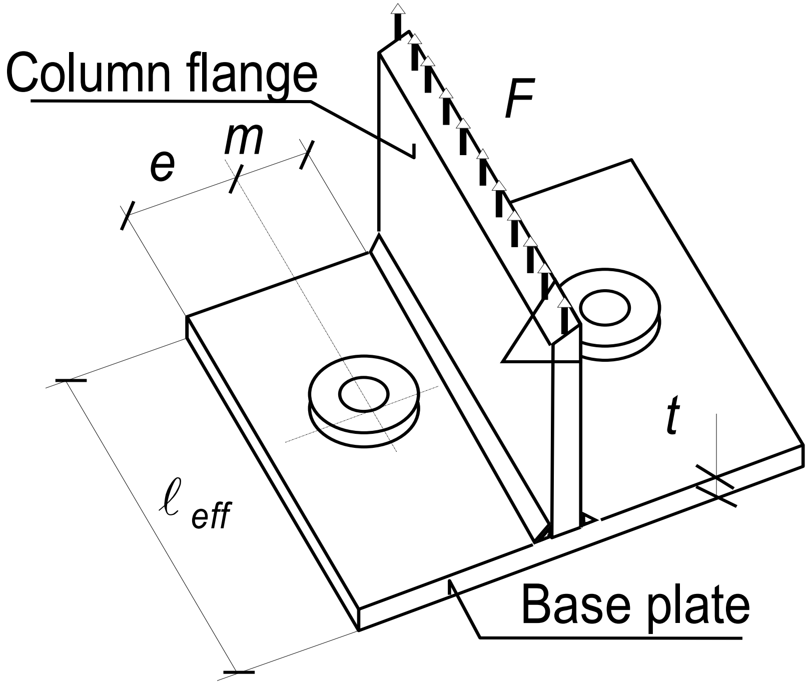
Component anchor bolts in tension and base plate in bending

T-stub created by the base plate, column flange/web and anchor bolts behaves differently compared to the T-stub created by end plate, beam flange/web and bolts in the bolted end plate connection because

- Base plate is thicker
- Anchor bolt free length is longer





When the prying force may not develop?

The base plate contact to concrete block depends on ration between bolt tensile stiffness and base plate bending stiffness.

Prying forces may develop if

$$L_{\mathrm{b}} \leq \frac{8{,}82 \cdot m^3 \cdot A_{\mathrm{s}}}{L_{\mathrm{eff}} t^3}$$

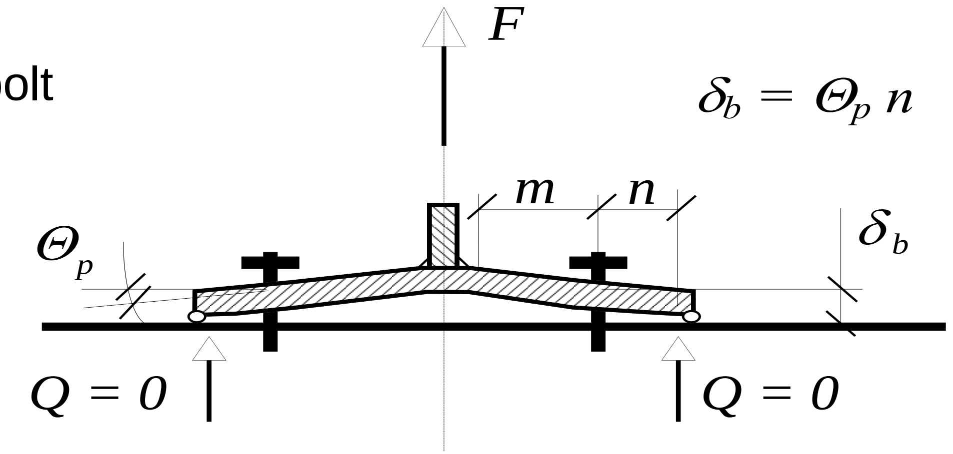
where

L_b is the anchor bolt elongation length, taken equal to the grip length (total thickness of material and washers), plus half the sum of the height of the anchor bolt head and the height of the nut, or the anchor bolt length, taken equal to the sum of 8 times the nominal anchor bolt diameter, the grout layer, the plate thickness, the washer and half the height of the nut,

A_s is the tensile stress area of the anchor bolt

t is the base palte thickness

L_{eff} is the T stub effective lenght



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Failure mode 1-2 without prying

The failure mode 1-2 is derived to avoid contact of the base plate to the concrete surface.

Design resistance for failure mode 1–2 is governed by plate failure

$$F_{T,1-2,Rd} = \frac{2\,M_{pl,1,Rd}}{m}$$

where m is the lever arm of the anchor bolt.

$$M_{pl,1,Rd} = 0{,}25\,\ell_{eff}\,t_f^{\,2} / \gamma_{M0}$$

is the plastic moment resistance of the base plate with

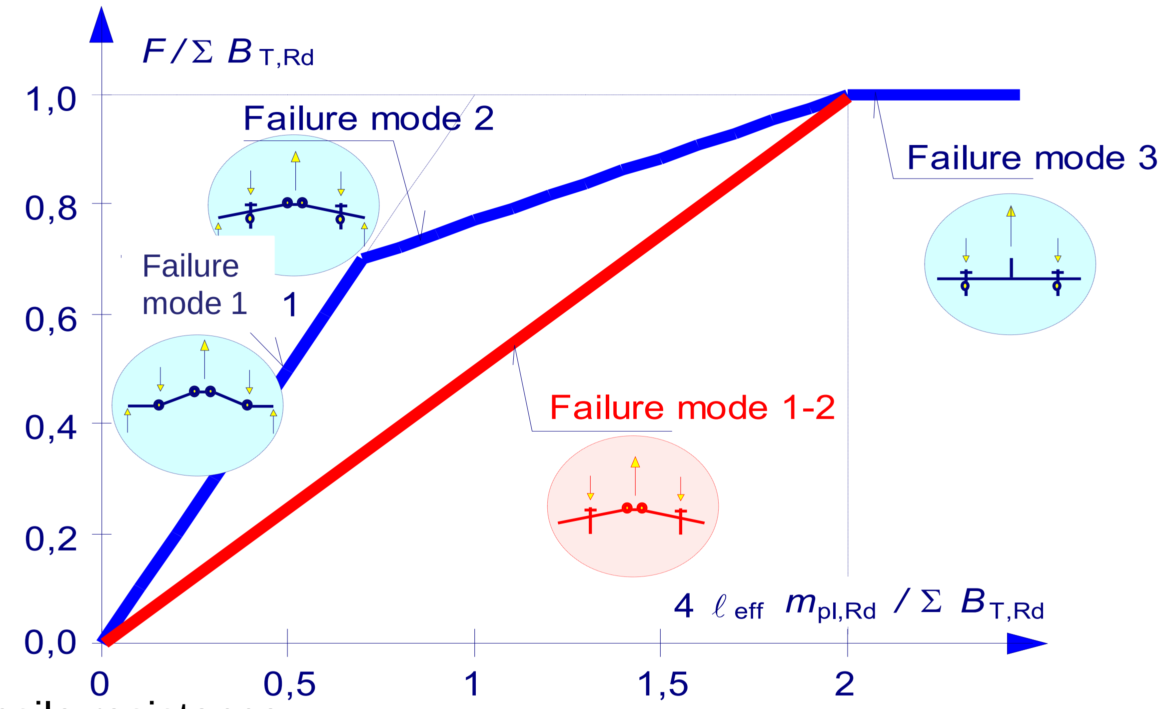
ℓ_{eff} is the effective length of the T-stub and

t_{eff} is the base plate thickness.

Graphical representation of the failure mode 1-2

of the T-stub of anchor bolts in tension and base plate in bending

The difference between failure mode 1 and 2 and failure mode 1-2 is shown on the diagram below, where on vertical axes is acting force F divided by the anchor bolts resistance and on horizontal axes is T-stub bending resistance of base plate divided by the anchor bolts resistance.



$B_{t.Rd}$ is anchor bolt tensile resistance

$m_{pl,Rd}$ is base plate bending resistance of unique length

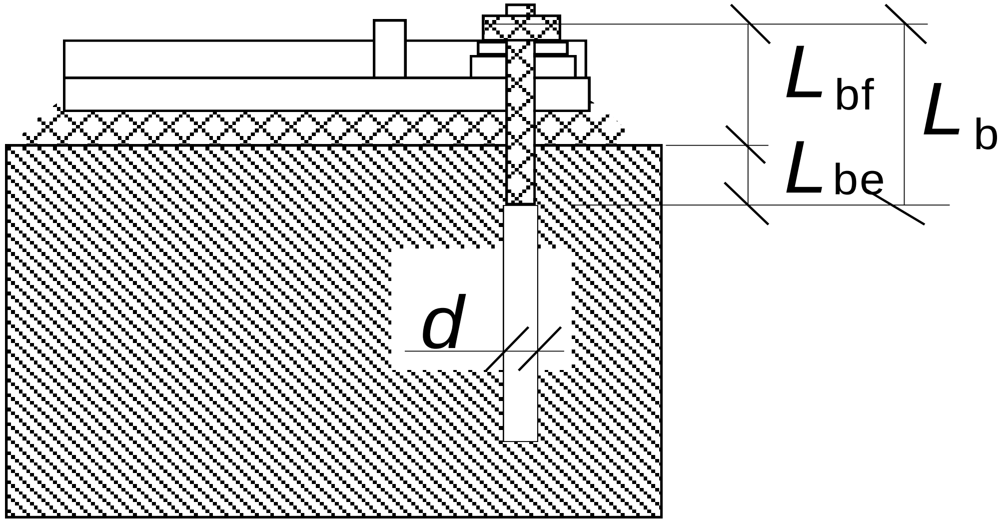
Anchor bolt effective length L_{eff}

Anchor bolt effective length L_{eff} consists of bolt free length L_{bf} and free embedded length L_{be} .

$$L_{eff} = L_{bf} + L_{be}$$

$$L_{eff} \approx 8\ d$$

where d is anchor bolt diameter.



Effective length of T-stub is different in case of prying/no prying

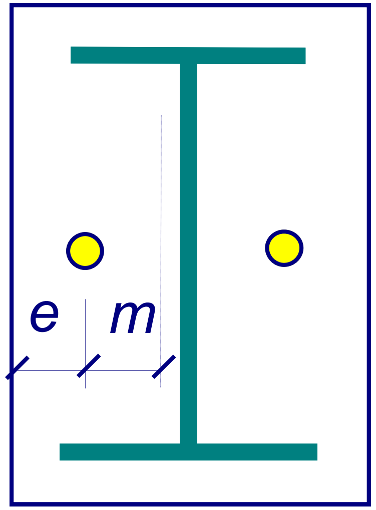
E.g. for base plate with bolts inside the flanges is the effective length

- in prying case

$$\ell_1 = 2\,\alpha\,m - (4\,m + 1{,}25\,e)$$
$$\ell_2 = 2\,\pi\,m$$

- in no prying case

$$\ell_1 = 2\,\alpha\,m - (4\,m + 1{,}25\,e)$$
$$\ell_2 = 4\,\pi\,m$$



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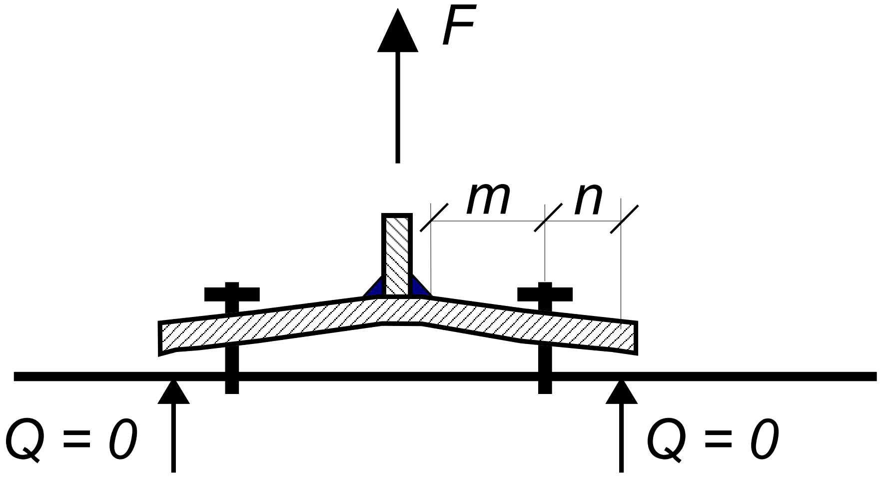
Stiffness is different in case of no prying

The stiffness coefficient for plate without prying is derived the stiffness coefficient for plate as

$$k_p = \frac{0{,}425\,\ell_{eff}\,t^3}{m^3}$$



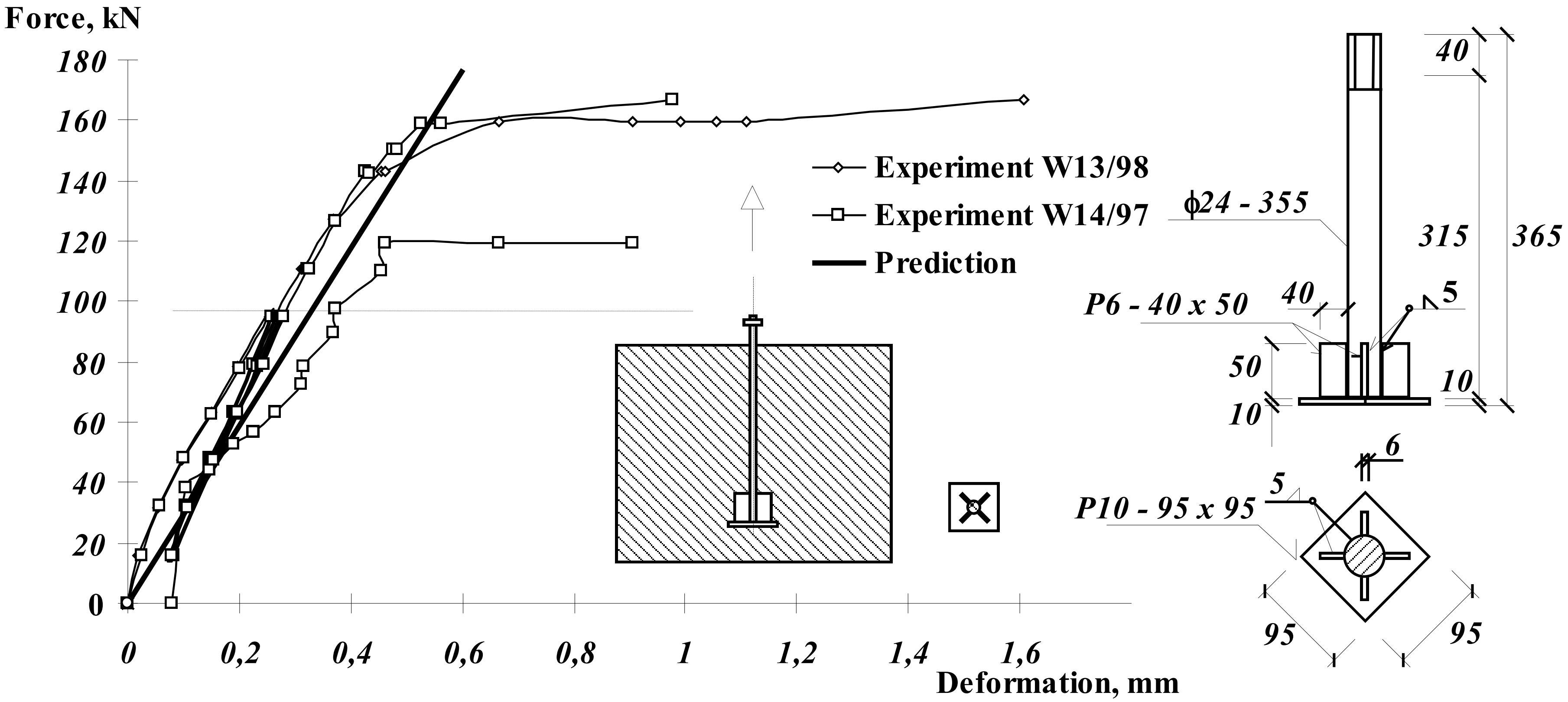
and for anchor bolt as

$$k_b = 2{,}0\,\frac{A_s}{L_b}$$

where t is the base plate thickness

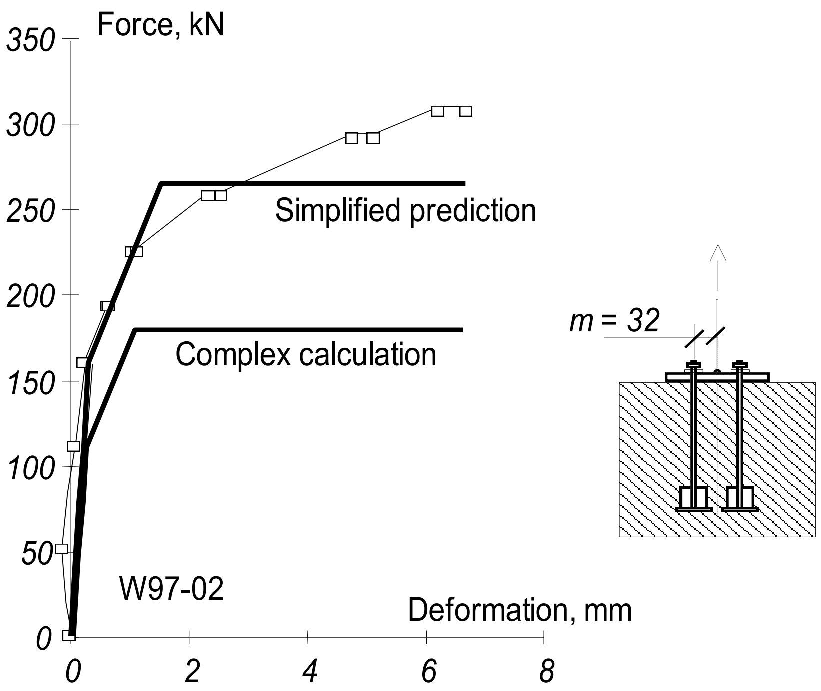
Comparison to experiments

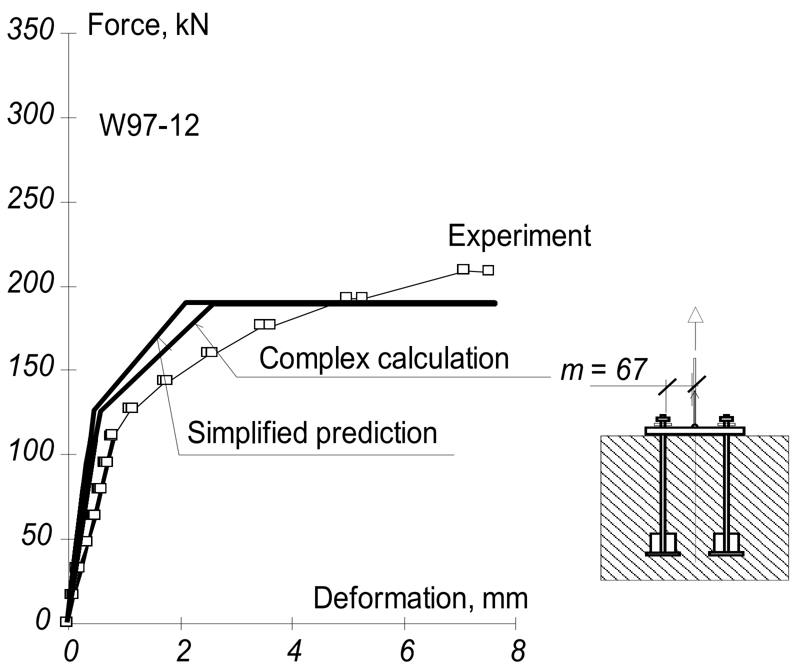
- The model of anchor bolt in tension is validated against the experiment in Figure below and the good prediction of the resistance and stiffness of the current models is shown.



Comparison to experiments

The model of the T-stub of component anchor bolt in tension and base plate in bending is validated against the experiment in Figures below and the good prediction of the resistance and stiffness of the current component model is shown.





Bending resistance

- The calculation of the column base resistance is based on the plastic equilibrium of forces on the cross section created by anchor bolts in tension and part of the concrete under base plate in compression.

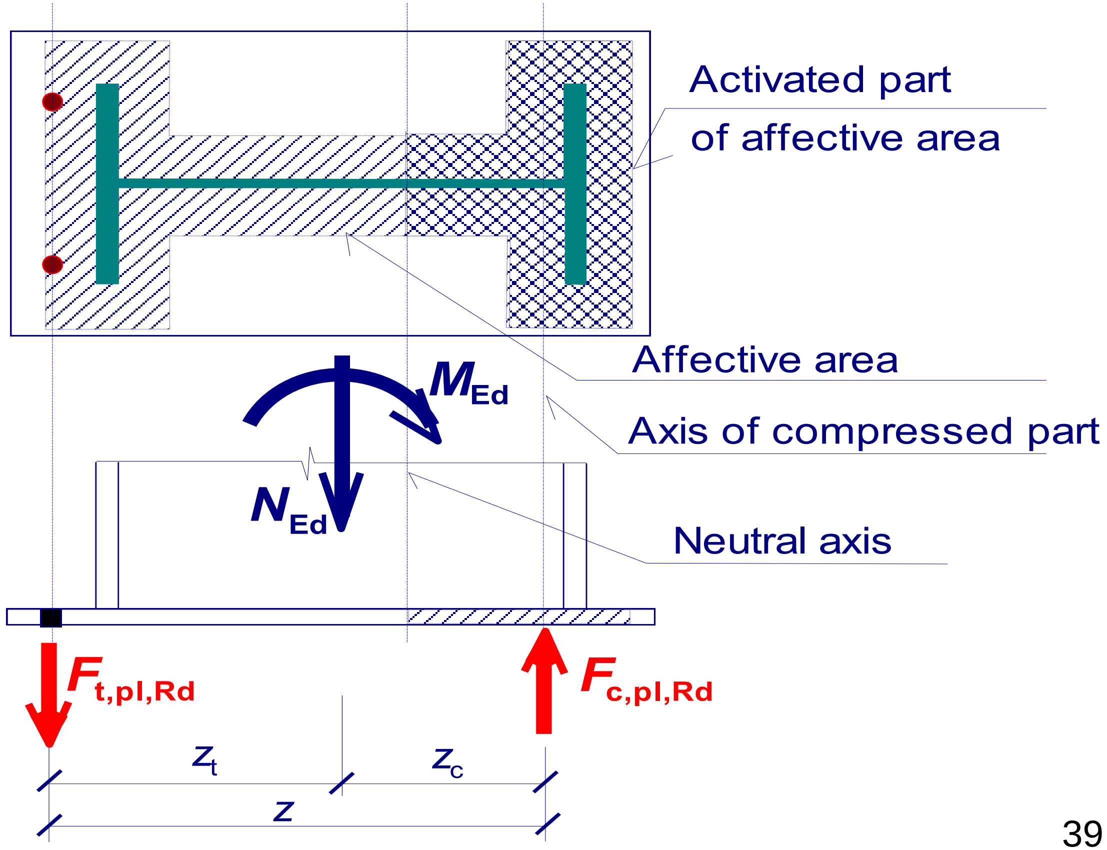
$$\frac{M_{\mathrm{Ed}}}{z} - \frac{N_{\mathrm{Ed}}\, z_{\mathrm{c}}}{z} = F_{\mathrm{t,pl,Rd}}$$

$$\frac{M_{\mathrm{Ed}}}{z} + \frac{N_{\mathrm{Ed}}\, z_{\mathrm{t}}}{z} = F_{\mathrm{c,pl,Rd}}$$

Then, the column base

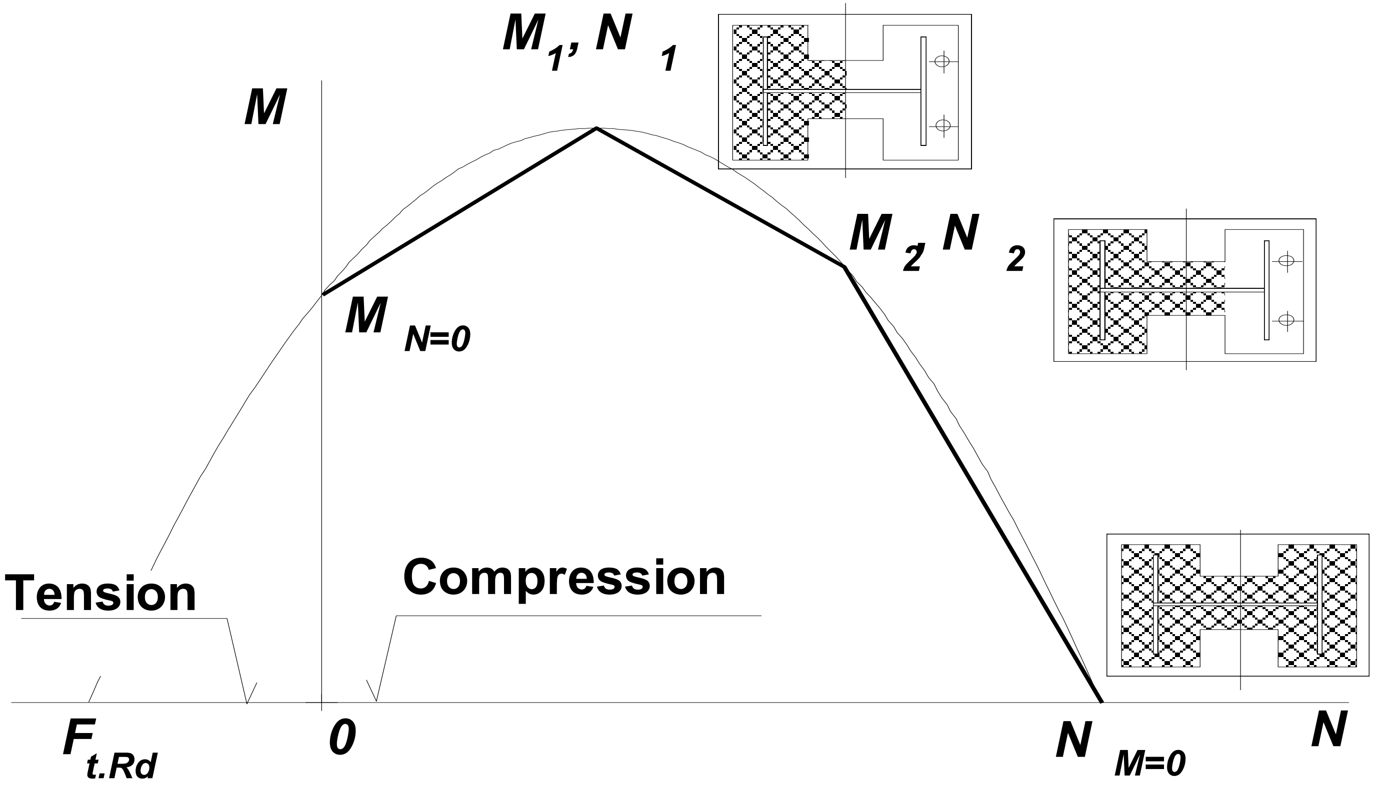
moment resistance M_{Rd} is

$$M_{\mathrm{Rd}} = \min \begin{Bmatrix} F_{\mathrm{t,Rd}} \cdot z + N_{\mathrm{Ed}} \cdot z_{\mathrm{c}} \\ F_{\mathrm{c,Rd}} \cdot z - N_{\mathrm{Ed}} \cdot z_{\mathrm{t}} \end{Bmatrix}$$



Interaction diagram

- Moment – normal force interaction diagram describes the design resistance of base plate by changing the eccentricity of loading with significant point at changes of effective area.



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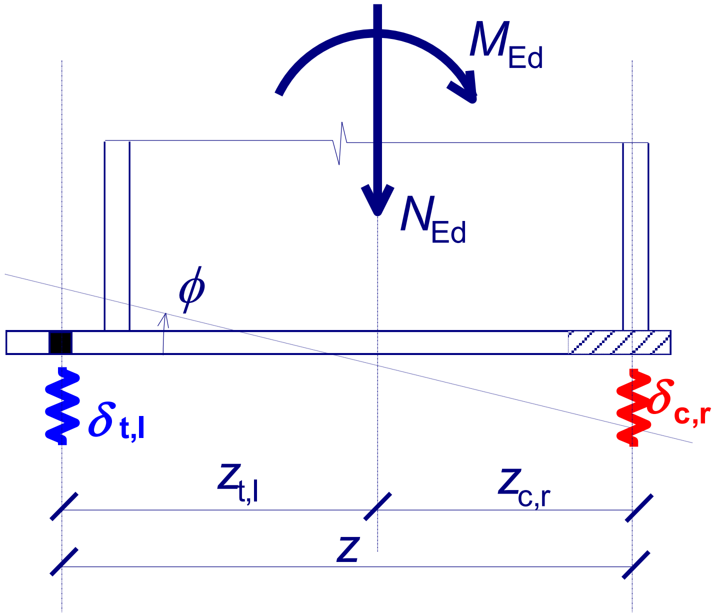
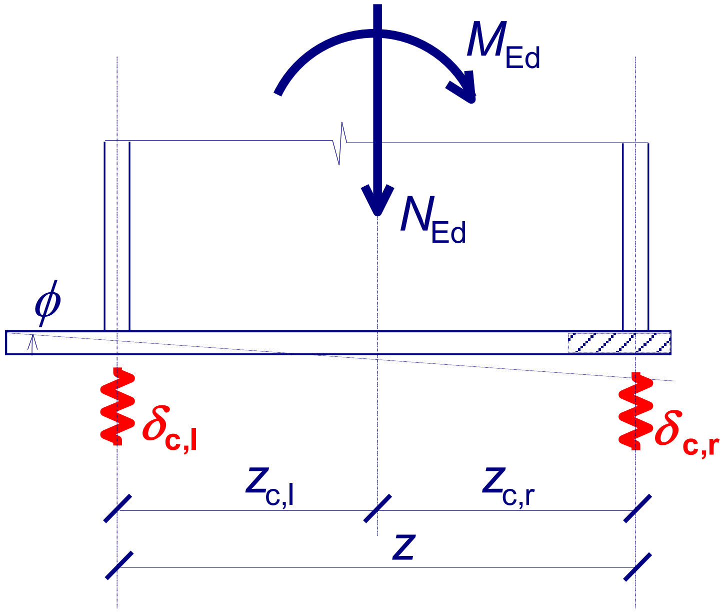
Bending stiffness

- The column base bending stiffness is derived on simplified model with acting compression force under column flange and tension force in centre of bolt row from the component deformation for two cases

Bolts are activated

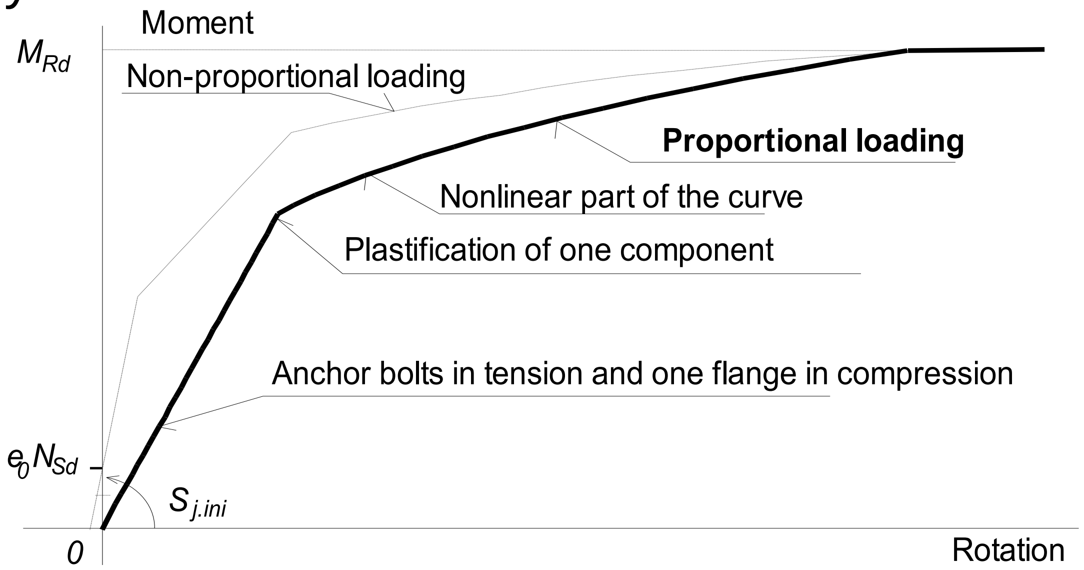


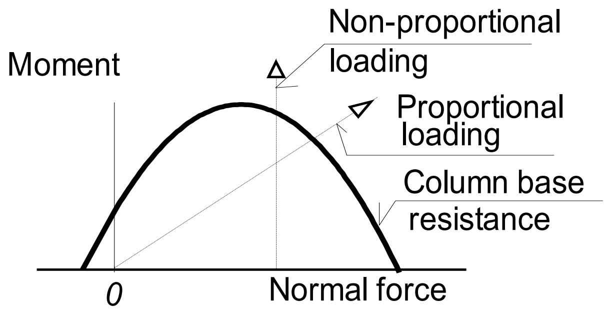
Bolts are not activated



History of loading

- The column base bending stiffness depends on history of loading. It is higher, if the column base is first loaded by compression and then by bending compared to, if it is loaded by reverse.

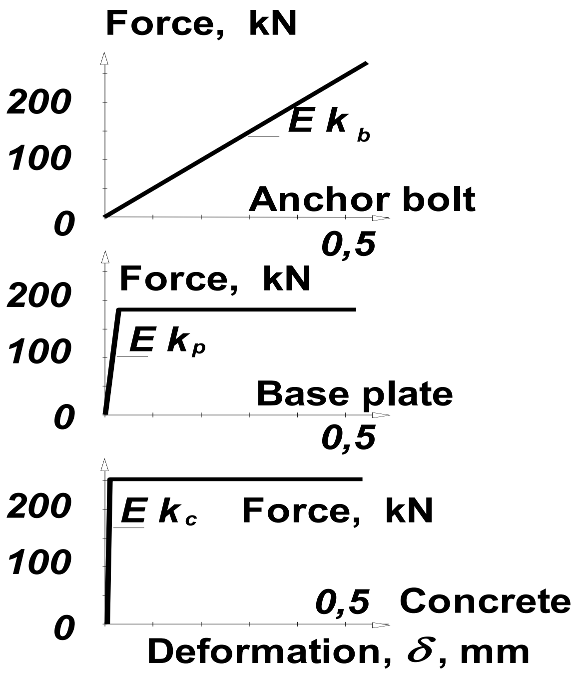




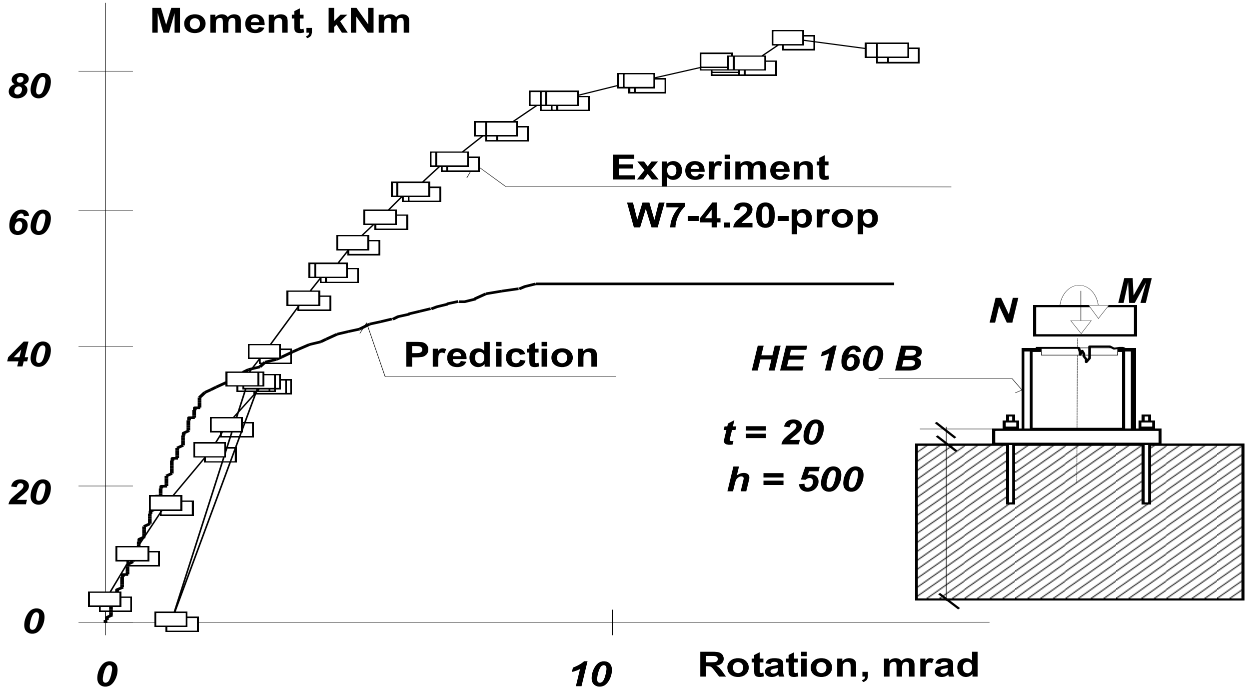
Comparison to experiment

- On Figures below is validated the model of the column base against the experiment to show the good prediction of the resistance and stiffness of the current component model.

Components

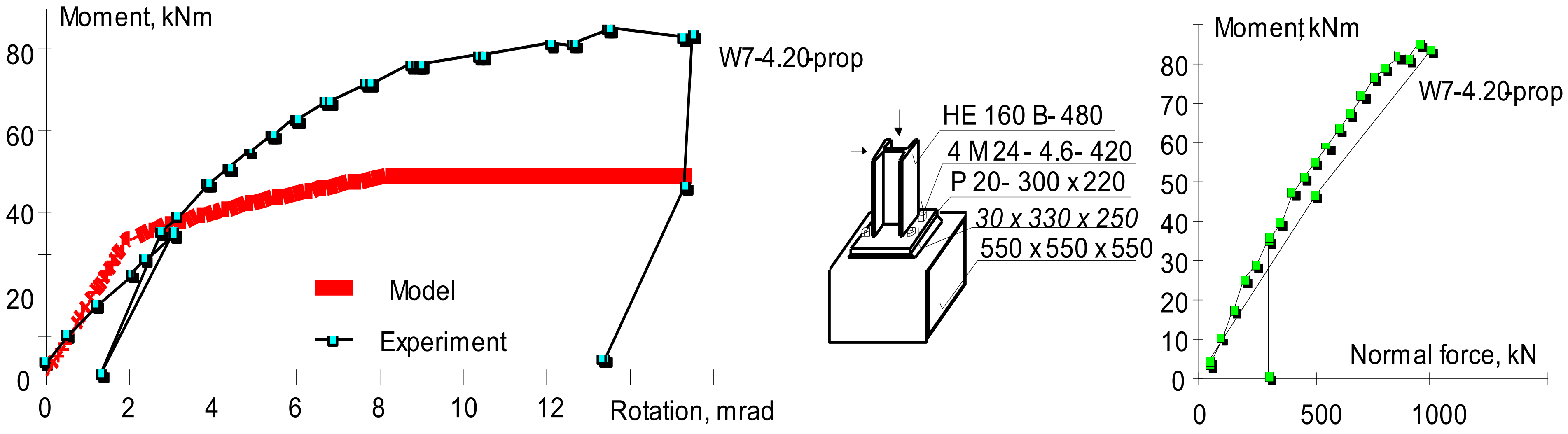


Assembly



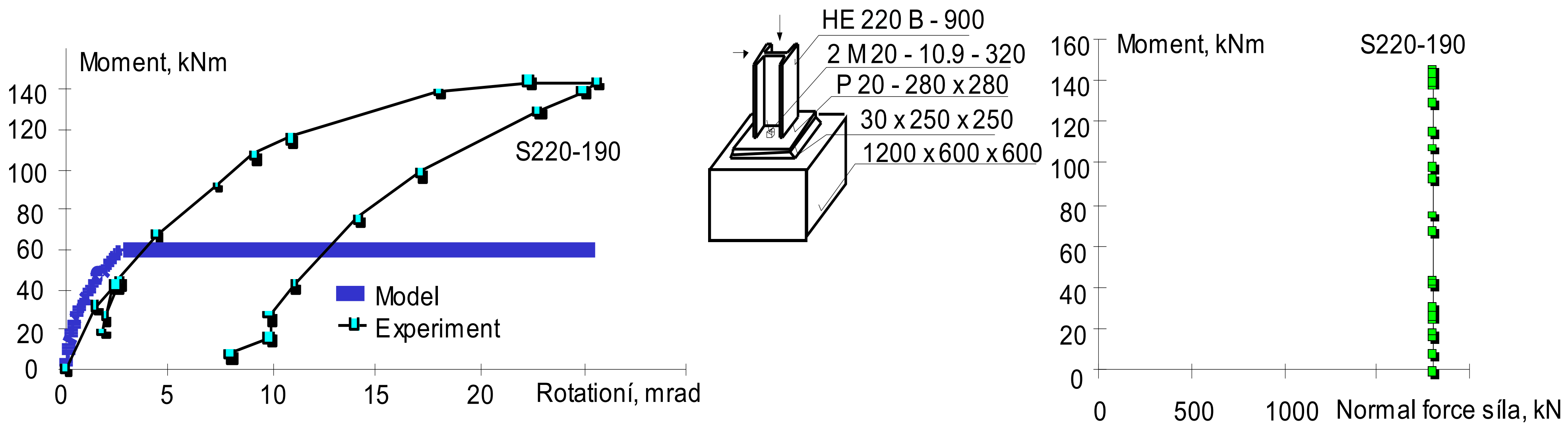
Comparison to experiment

- On Figure below is validated the model of the column base proportionally loaded by moment and normal force with the bolt steel failure mode against the experiment to show the good prediction of the resistance and stiffness of the current component model.



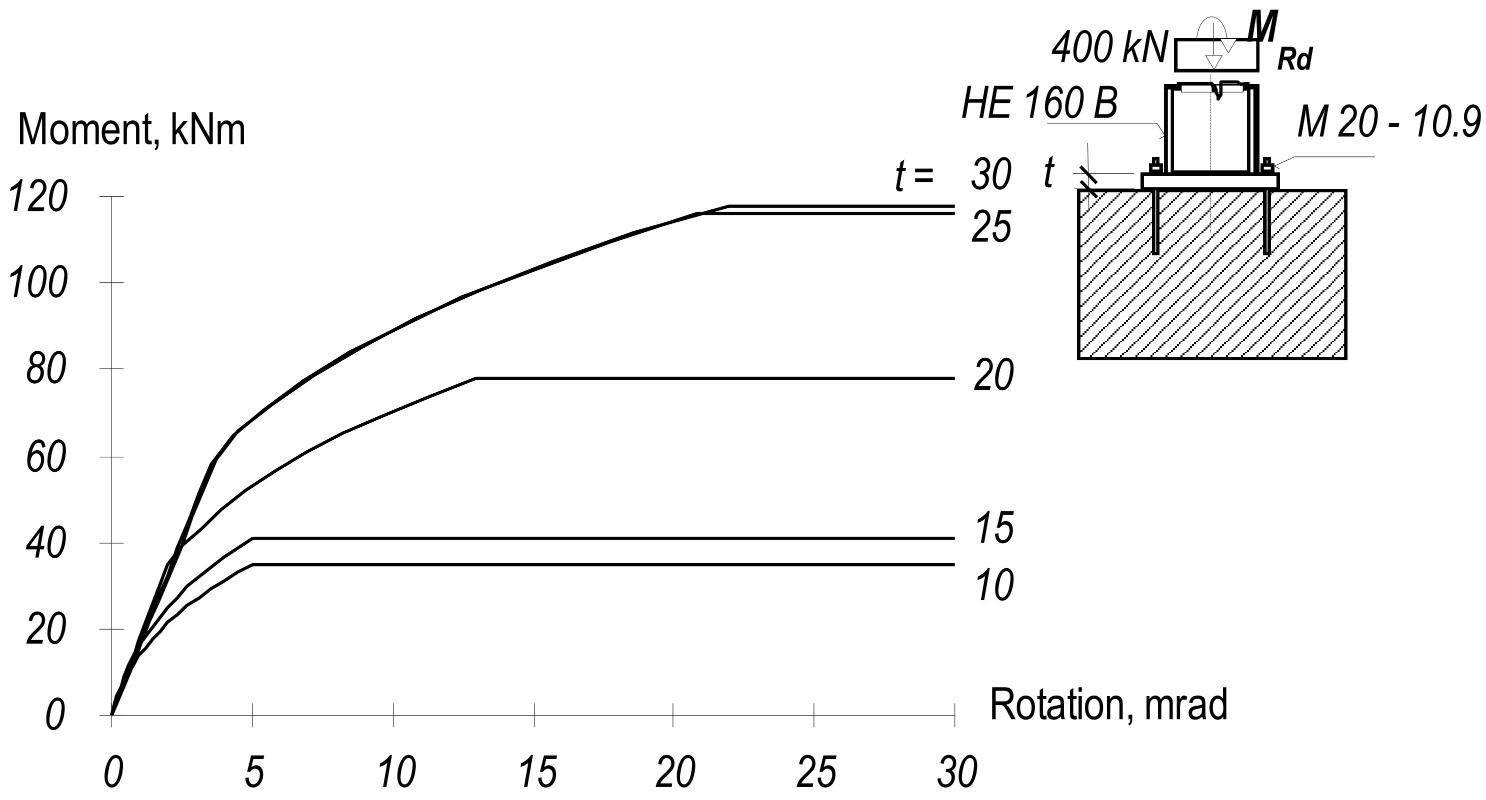
Comparison to experiment

- On Figure below is validated the model of the column base non-proportionally loaded by moment and normal force with the concrete cone failure mode against the experiment to show the good prediction of the resistance and stiffness of the current component model.



Sensitivity study

Figure below shows the sensitivity of the bending moment resistance and the bending stiffness of the column base proportionally loaded by normal force with eccentricity.
From base plate thickness are governing anchor bolts.



Assessment II

- What are the basic components on base plate?
- What are the major question in design of component in compression?
- What is the reason for introducing the joint coefficient?
- What is the reason of limiting the effective width of the base plate?
- What is the reason, that prying may in case of Failure mode 1-2 not develop?
- How is simplified the model of acting compression force for prediction of the column base stiffness?

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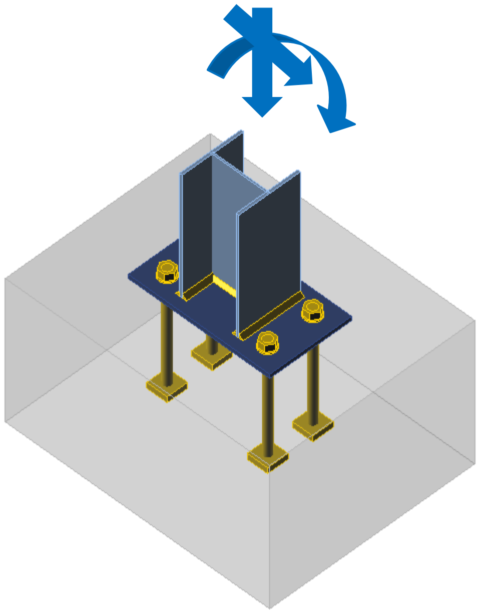
Component Based FEM

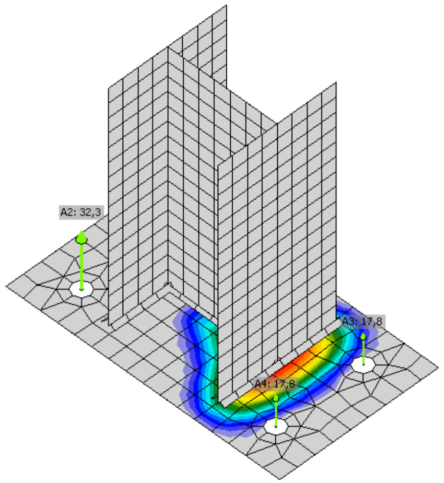
Lecture 4

Column base

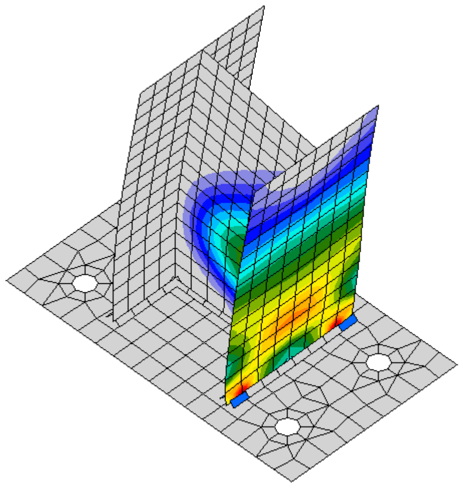
Concept of Component Based Finite Element Method for column bases

- Steel part of column base, column base, column, base plate and stiffeners are simulated by shell models.
  Resistance is limited by 5% of plastic strain.
- Concrete block is taken as component with elastic-plastic surface.
- Anchor bolts/welds are modelled as components.





Stress in concrete



Plastic strain in column

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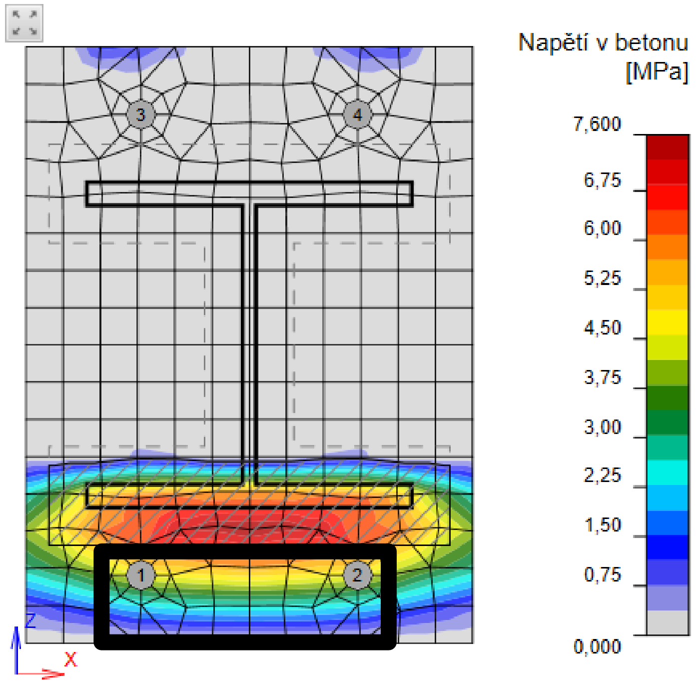
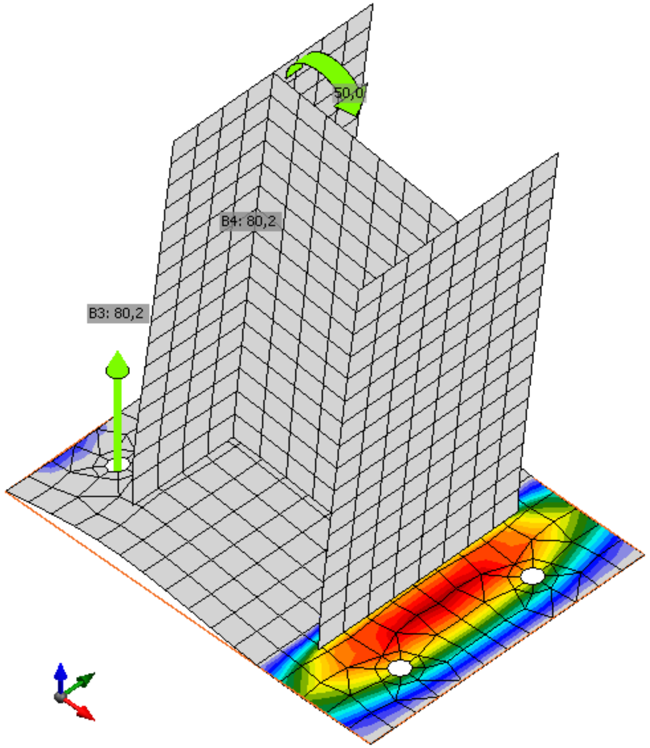
Component concrete in compression

For resistance is considered the part of the concrete block under effective area A_{eff} only using overlap c,
where the base plate deforms in its elastic stage, following the engineering assumption formulated in EN1993-1-8:2006.





Component anchor bolt in tension

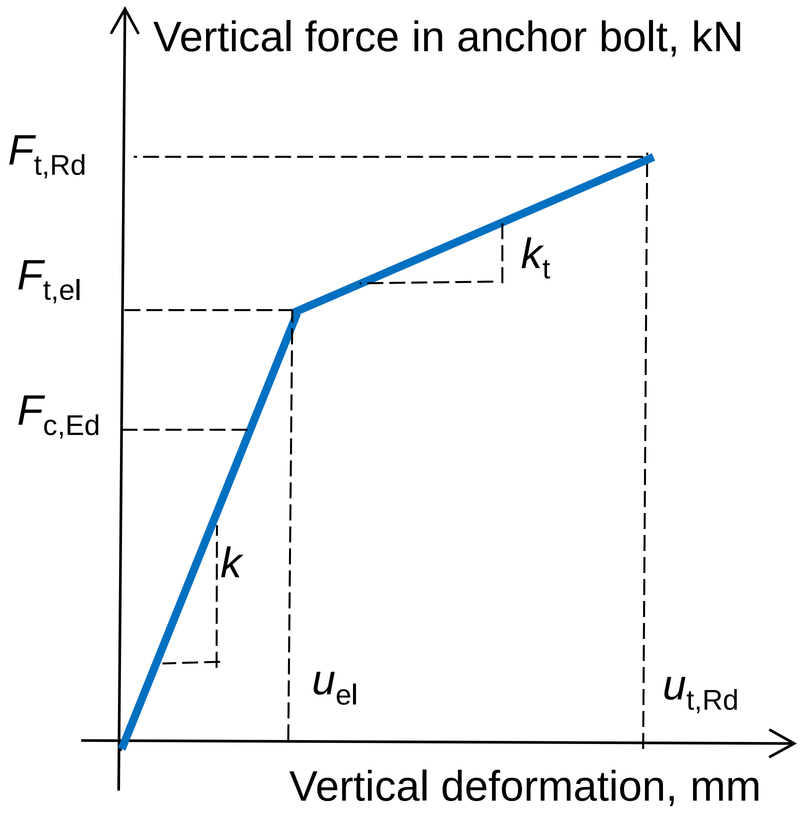
- The resistance of the anchor bolt in tension is taken from concrete components resistance and from the steel one.
- Maximum allowed plastic strain for anchor bolts ε_{mpb} is taken as 25 % of elongation till fracture.
- The stiffness in tension is calculated as

  $k = E\,A_s/L_b$,

  where

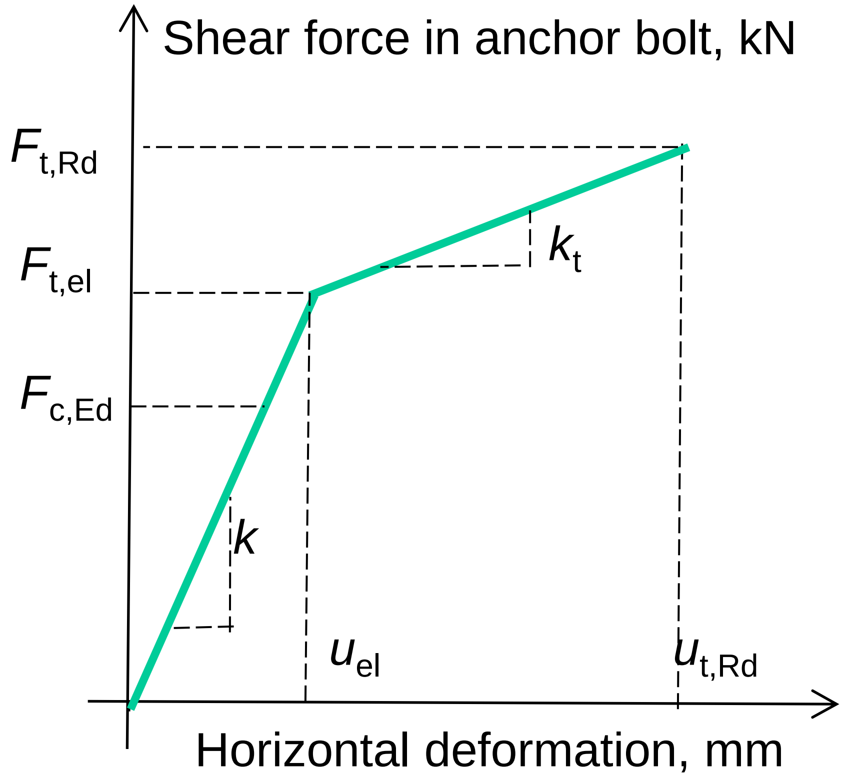
  A_s is tensile area of anchor bolt and

  L_b is the distance between the centers of the head and the bolt nut.

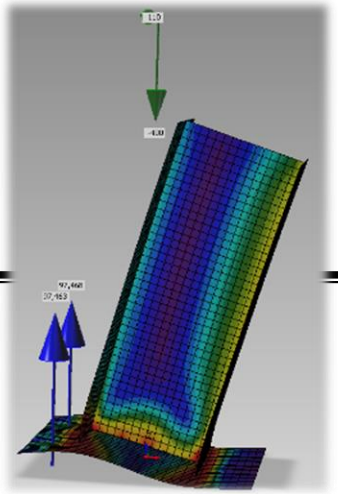


Component anchor bolt in shear

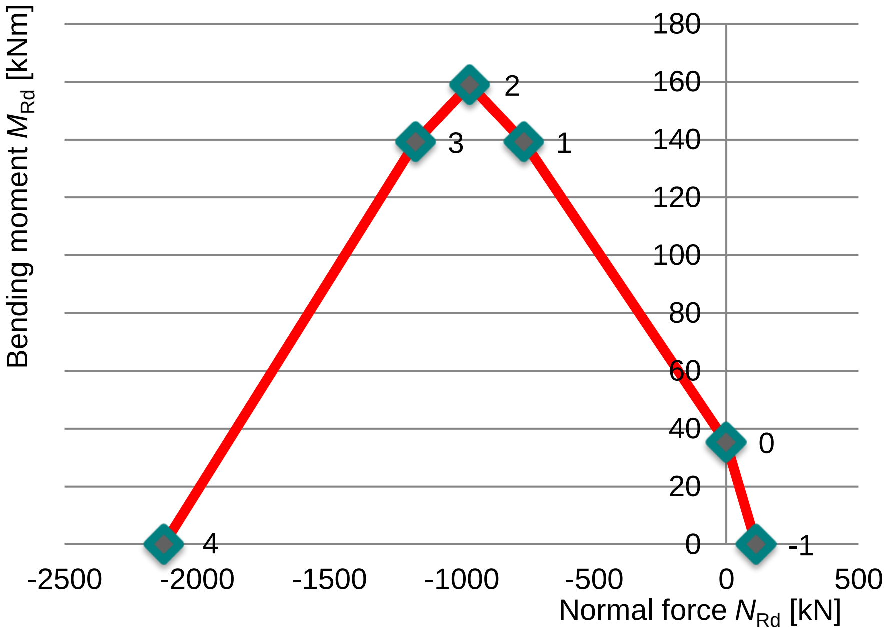
- The resistance of anchor bolt in shear is calculated according to EN1992-4:2018 and EN1993-1-8:2006.
- Stiffness of anchor bolt in shear includes bearing of concrete and bending of bolt.

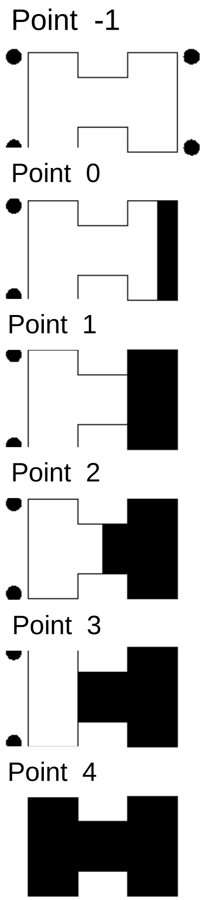


Normal force and bending moment interaction diagram



- The cross section under base plate consists of anchor bolts and contact to concrete.
- The significant points on interaction diagram reflects changes of geometry of compressed part.
- The cross section exposed to normal force and bending behaves like concrete column cross section of effective contact area.





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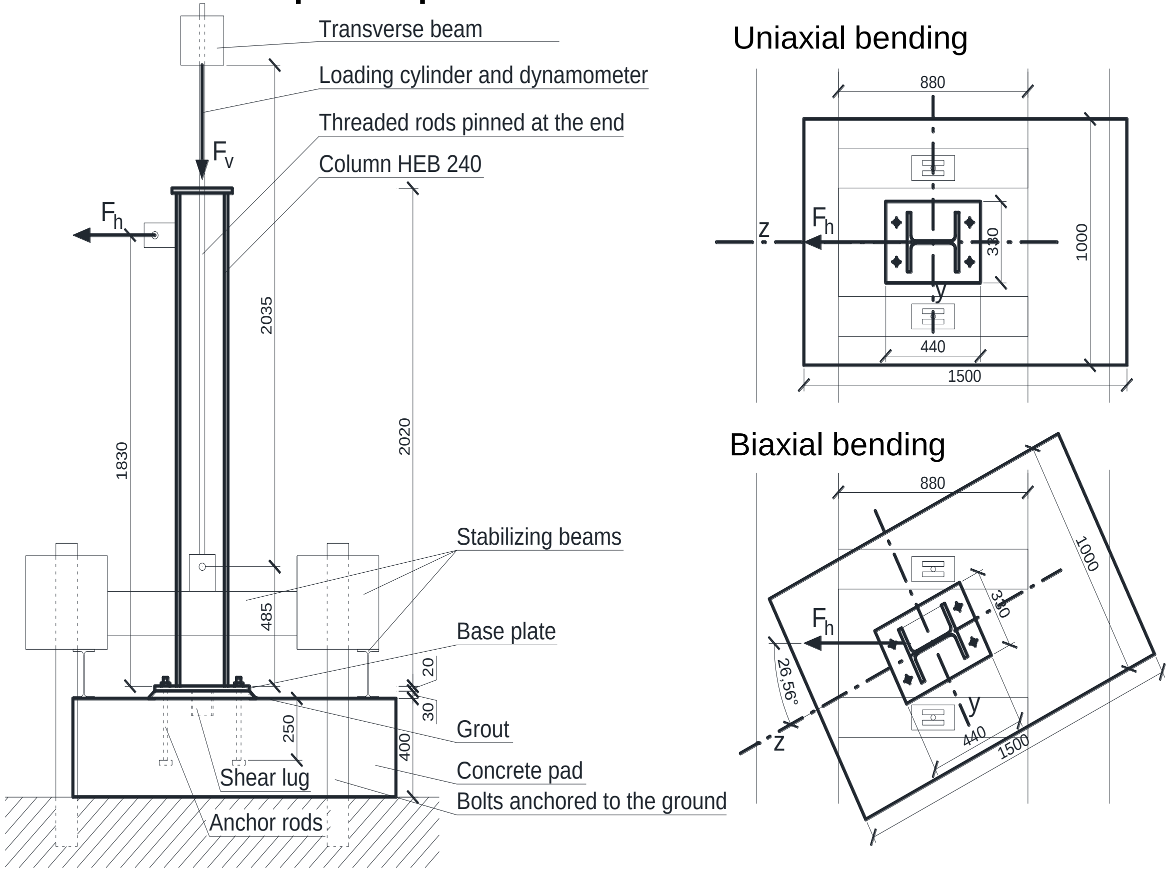
Experiments for validation

- For validation were prepared two experiments in uniaxial and two in biaxial bending at TU Brno.
- The experimental set ups is presented below.



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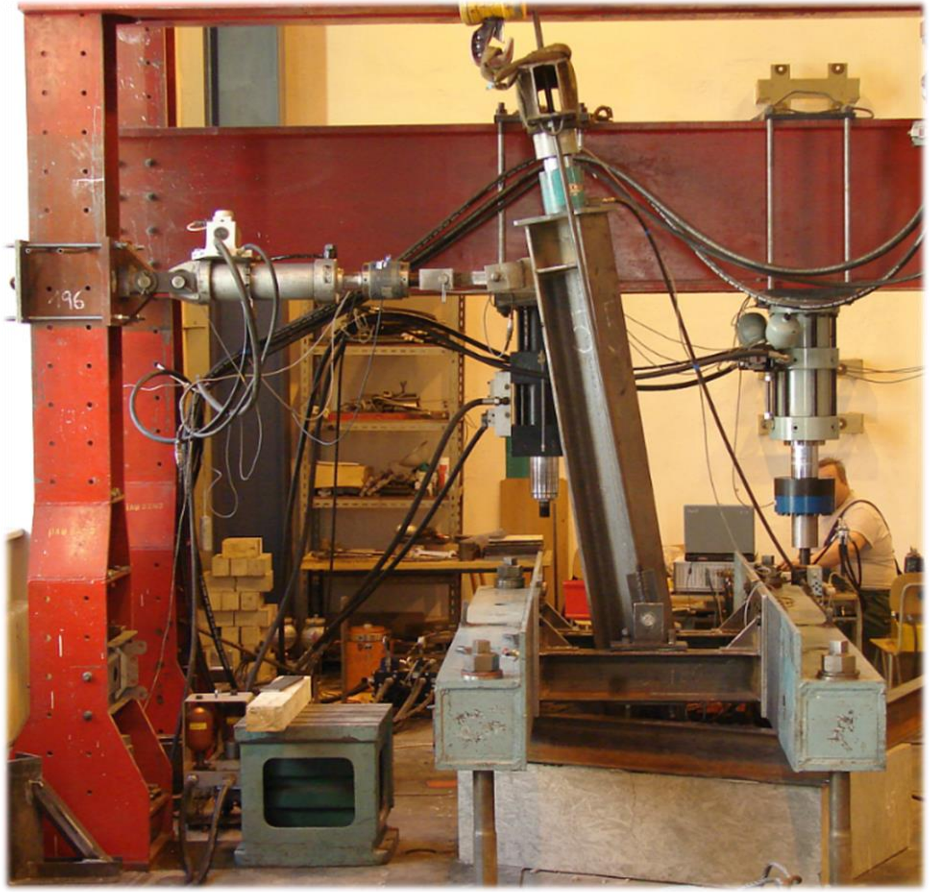
Experiment´s general data

- Column HEB 240
- Concrete block 1000x1200x9000 C20/25
- Base plate 330x440x20 S235
- Anchor bolts 4 x M20
- Grout 30 mm



Bending of set up in biaxial bending

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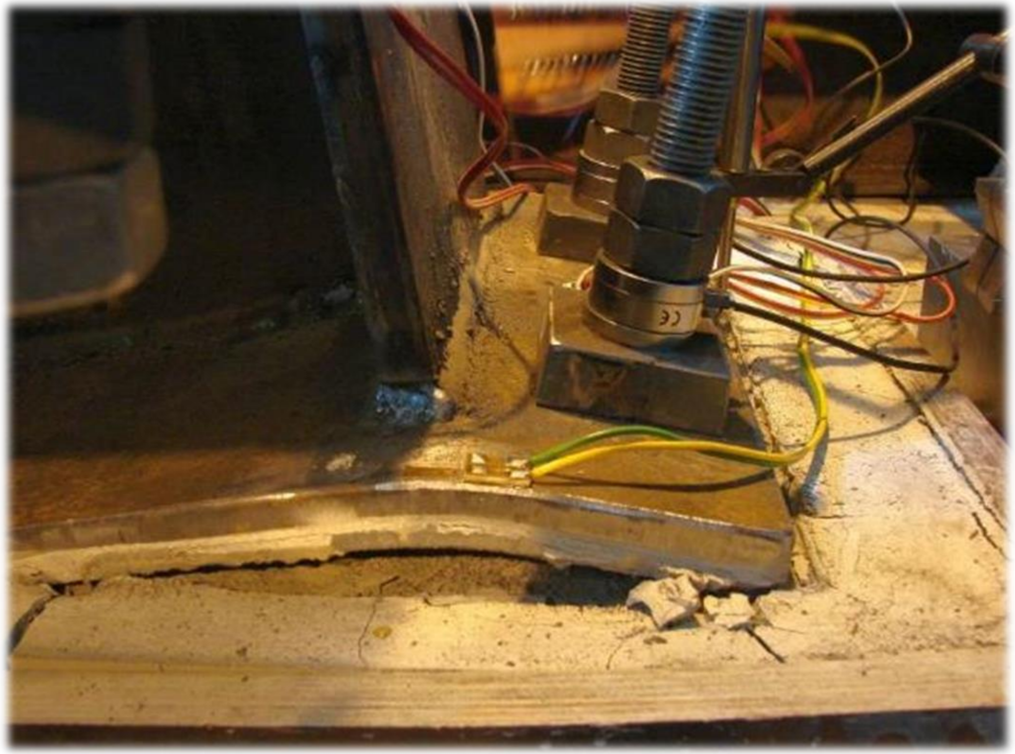
Behaviour of base plate in case of uniaxial bending

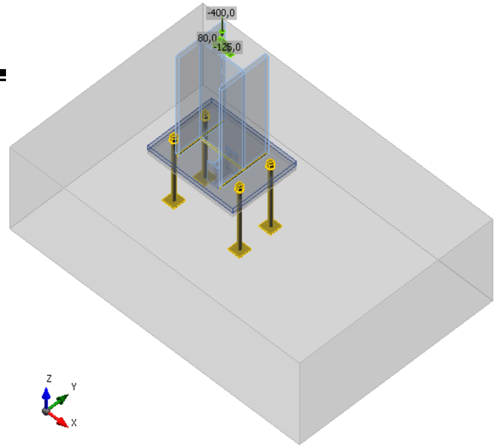
Set up in uniaxial bending

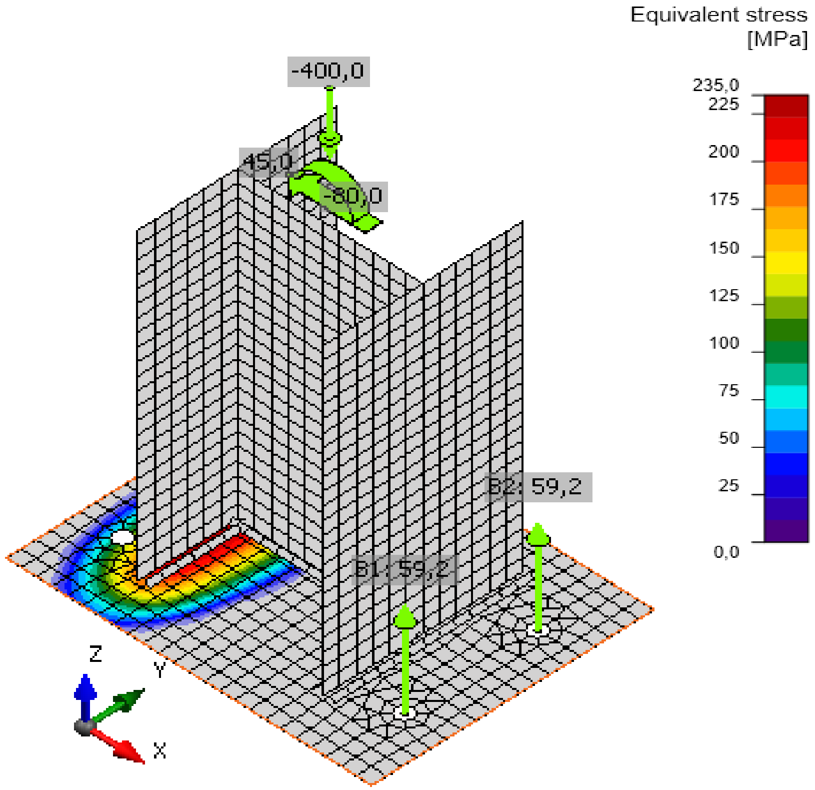


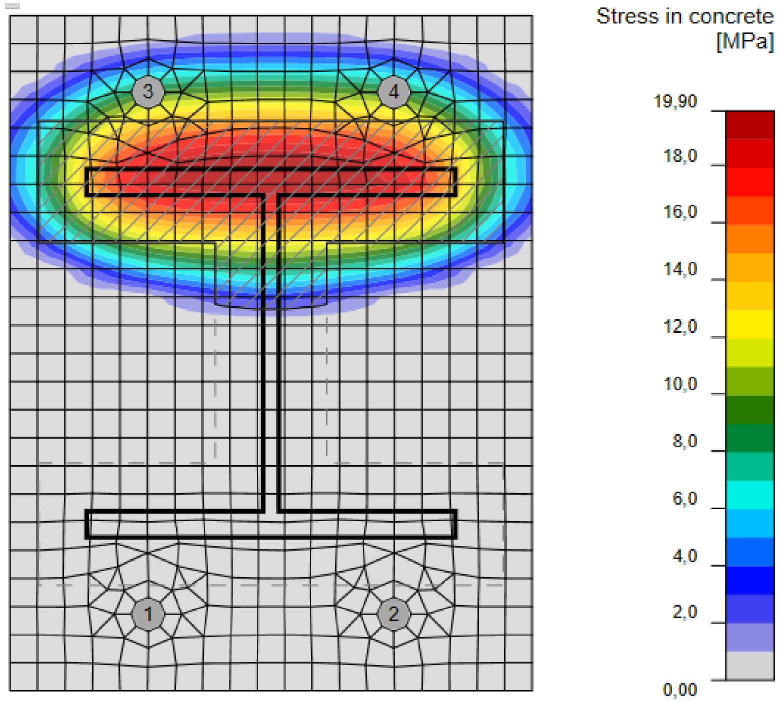
Deformed base plate

FE prediction of column base behaviour in uniaxial bending

- Figure below shows the equivalent stresses in base plate and in concrete calculated by CBFEM.







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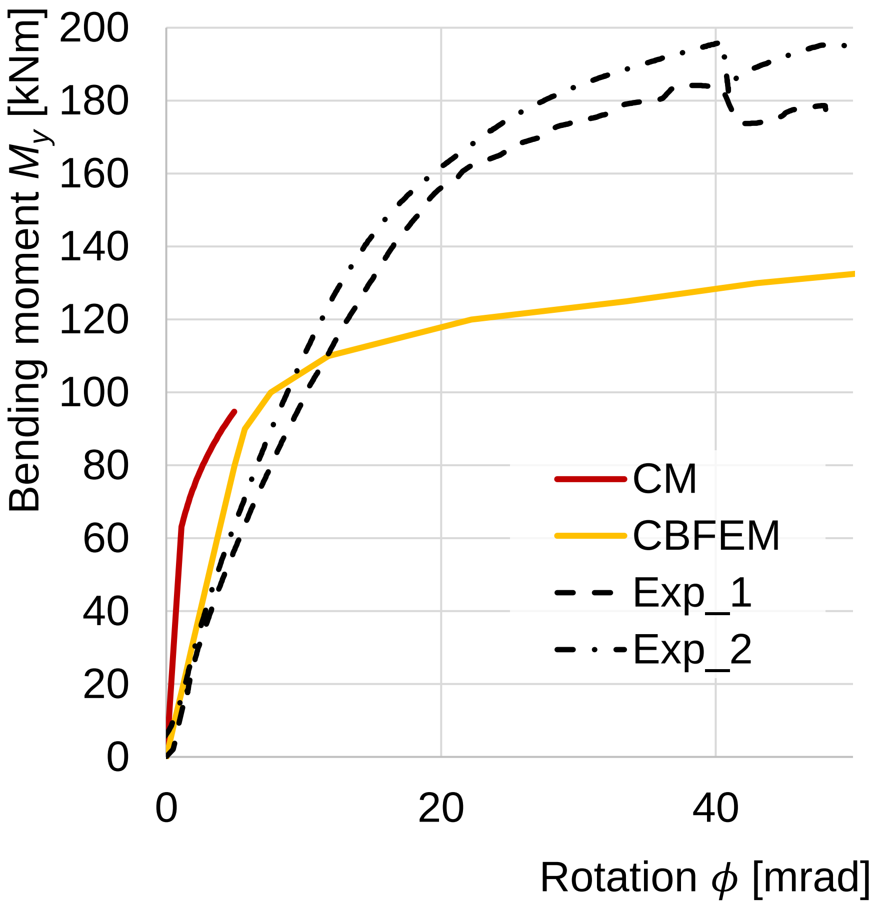
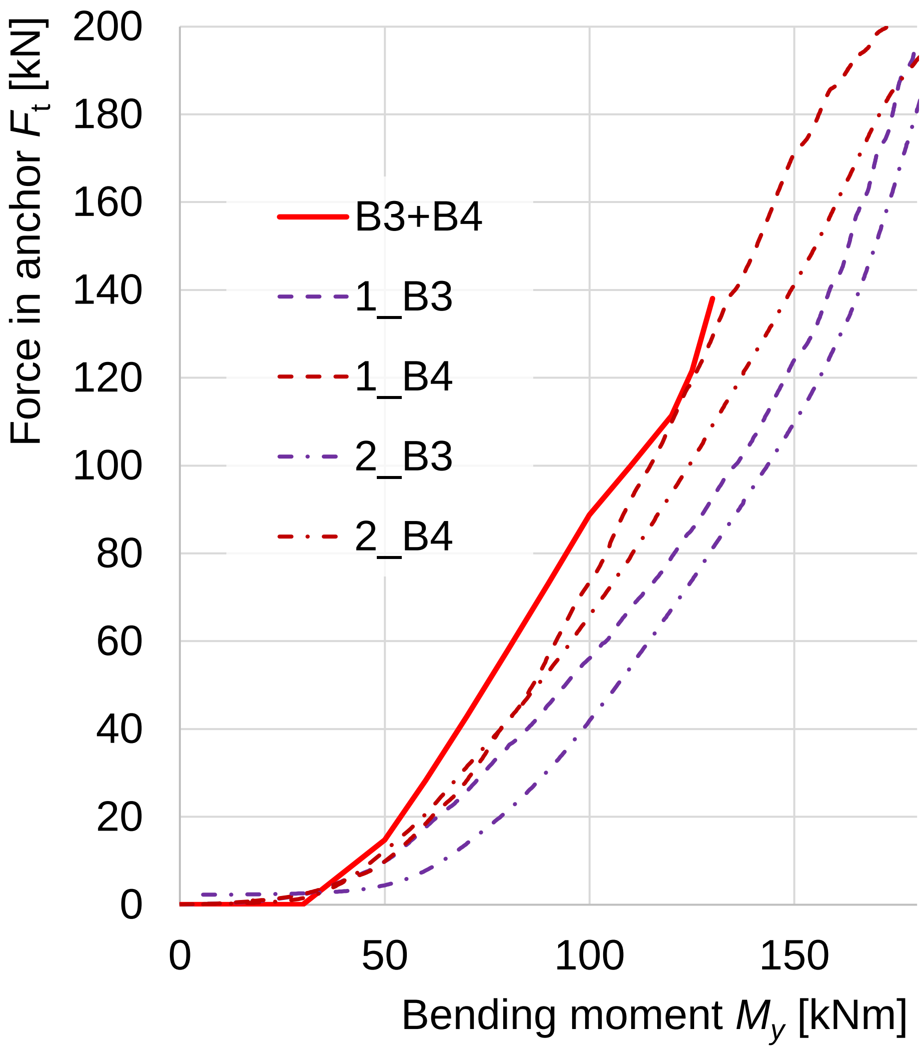
Validation of models to experiments in uniaxial bending



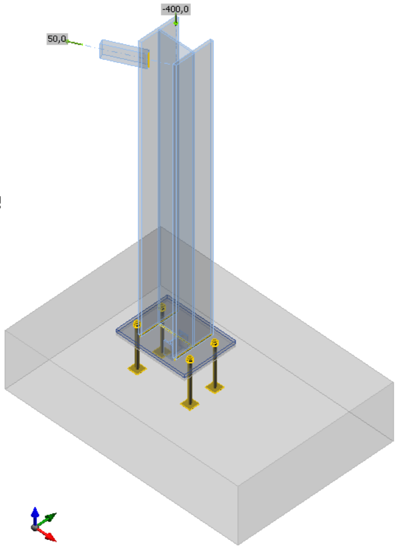
- Figure left shows on moment rotation diagram a good prediction capacity of resistance of both Component (CM) and Component Based FE model (CBFEM).
- CBFEM compared to CM predicts higher resistance. It includes real space stress in concrete.
- The bending stiffness of experiments is lower compared to prediction.
- The predictive model shows compared to experiments the safety due to conservative proposal of anchor bolt.

Validation of CBFE model to experiment in uniaxial bending

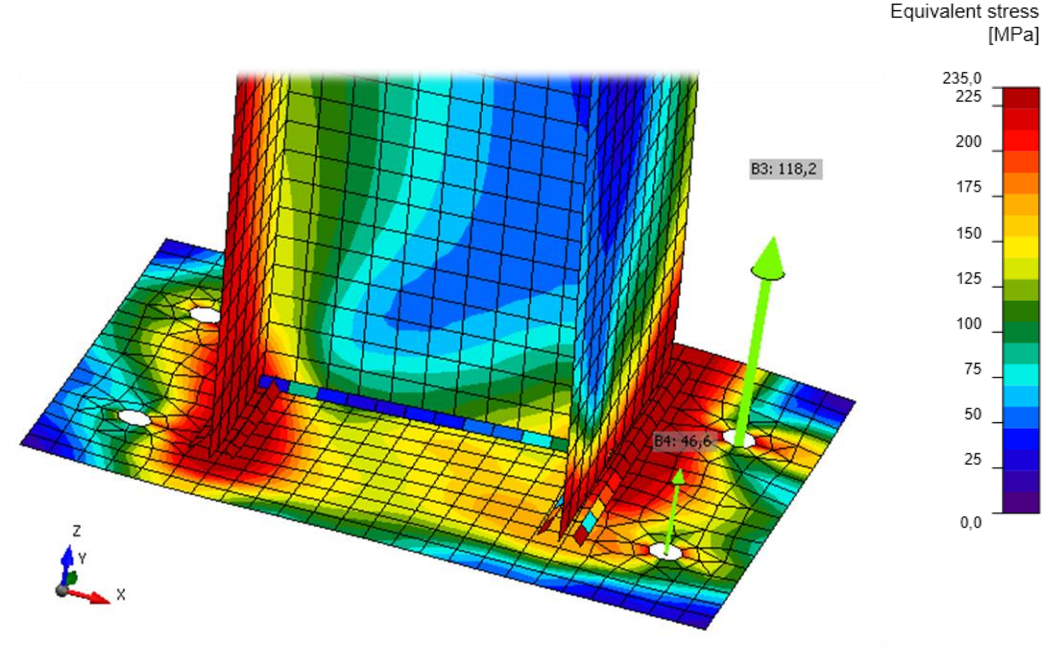


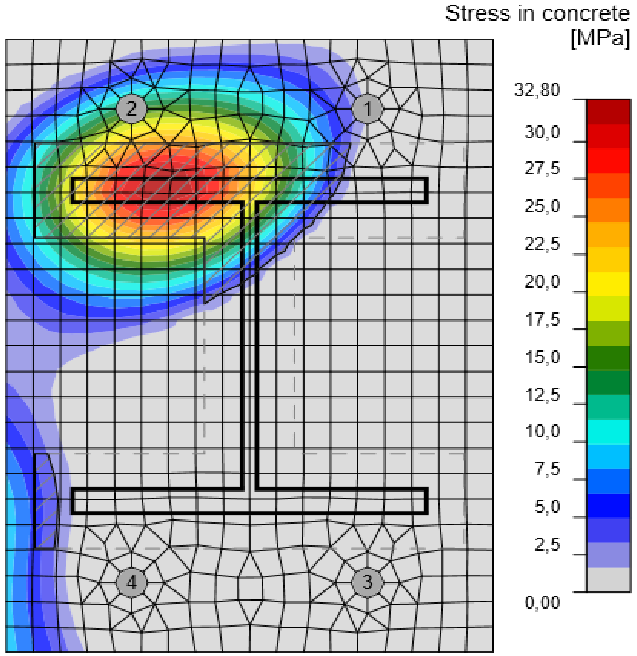
- Figure left shows on anchor force – bending moment diagram a good prediction capacity of Component Based Finite Element Model.
- The predicted bolt force is conservatively higher compared to measured ones on both experiments.

FEA model for column base in biaxial bending

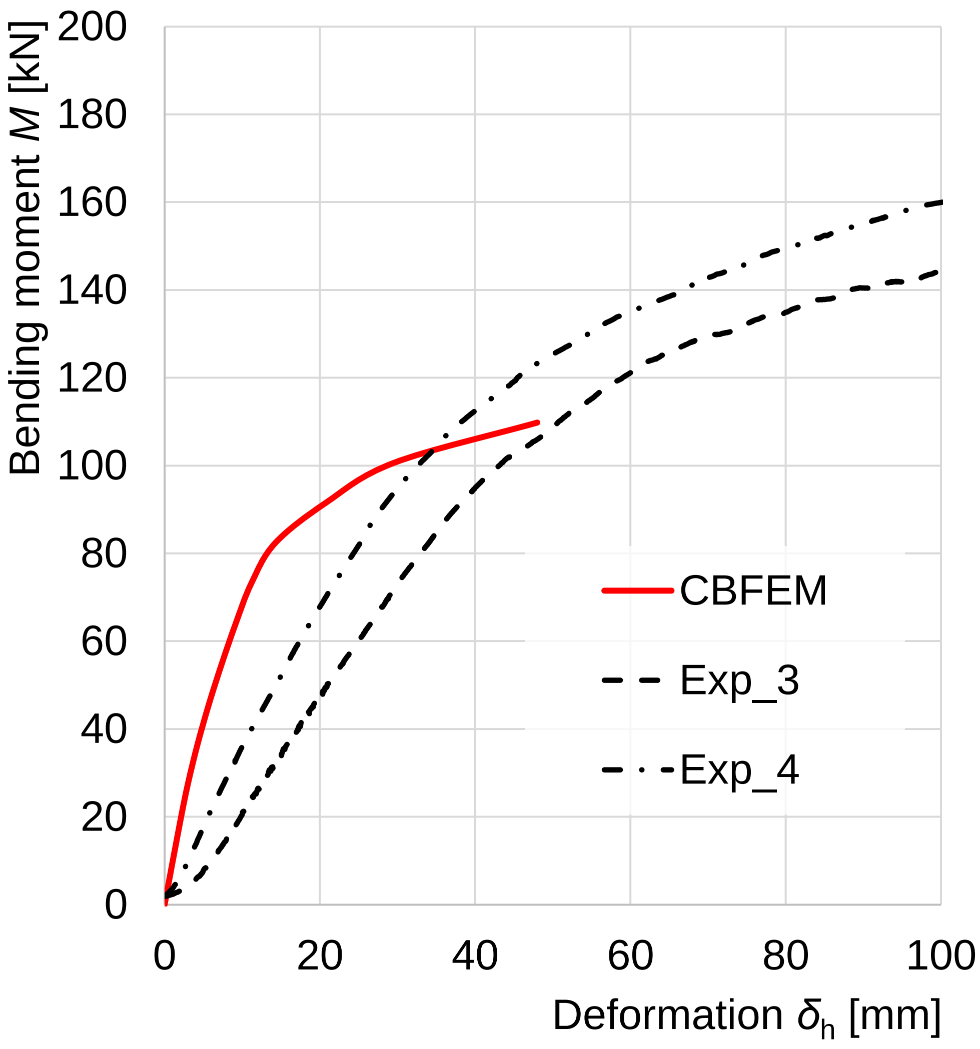


- Figure below shows the equivalent stresses in base plate and in concrete in Component Based FE model



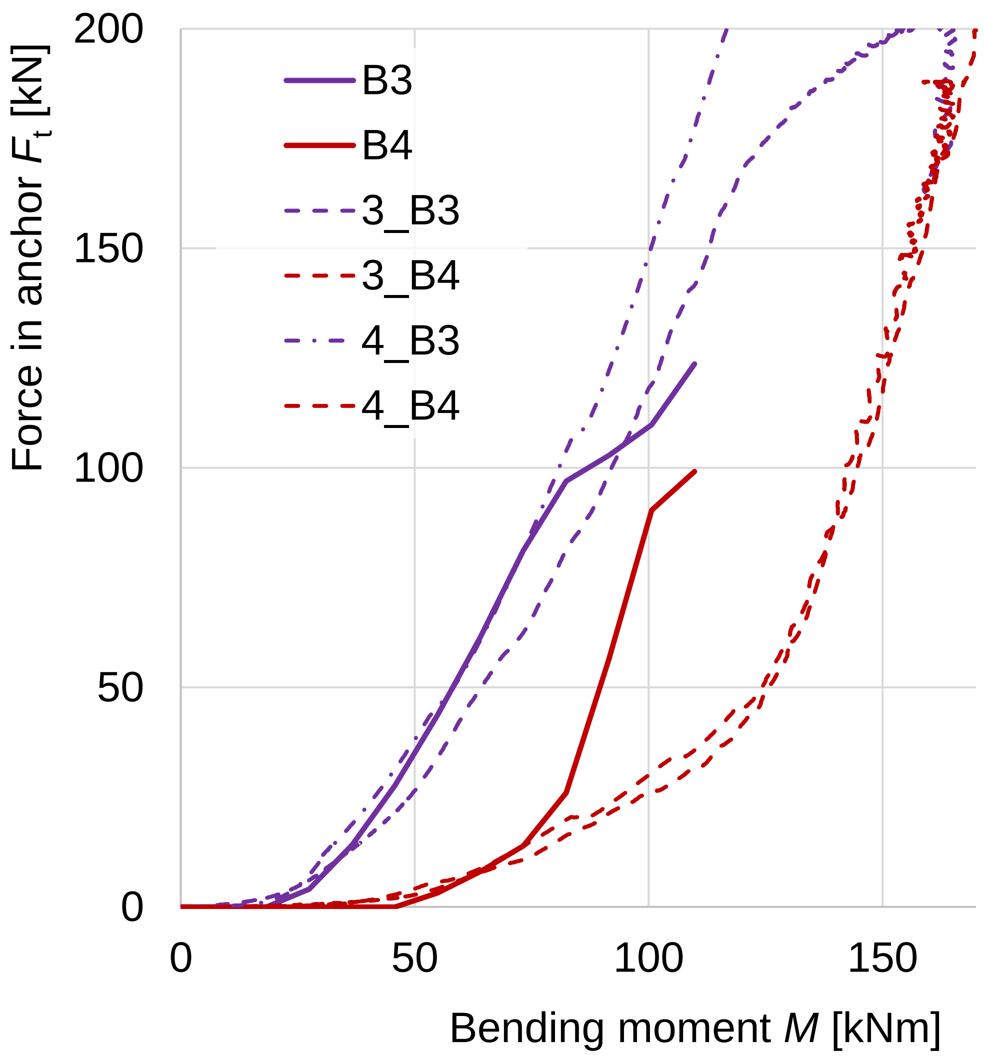


Validation of model to experiments in biaxial bending



- Figure left shows on moment rotation diagram a good prediction capacity of resistance of Component Based FE model.
- The bending stiffness of experiments is lower compared to prediction.
- The predictive model shows compared to experiments the safety due to a conservative proposal of anchor bolt.

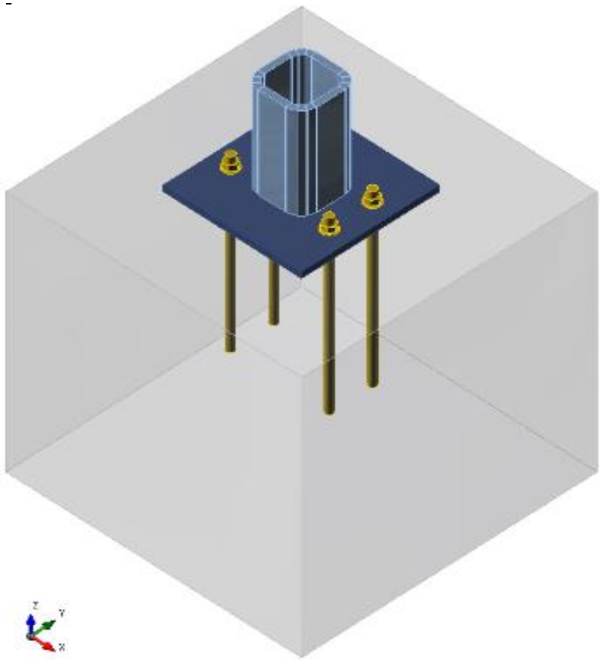
Validation of CBFE model to experiment in uniaxial bending

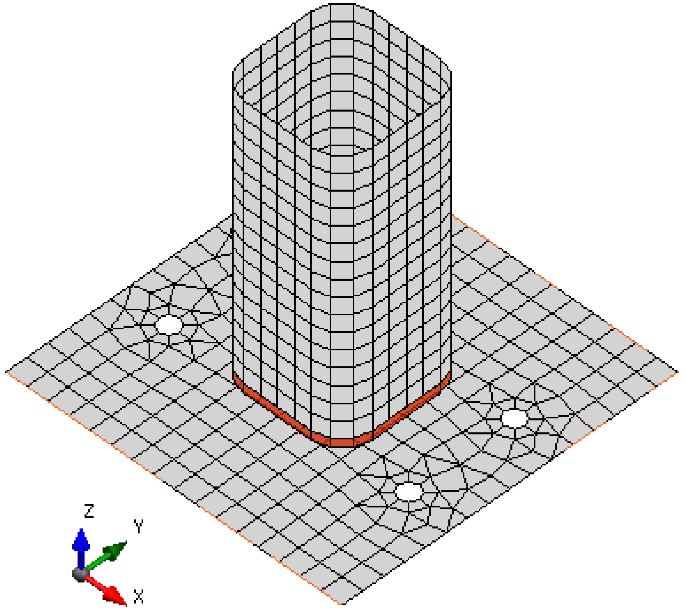


- Figure left shows on the anchor forces – bending diagram a good prediction capacity of Component Based FE model for the most loaded anchor bolt.
- The predicted bolt force is conservatively higher compared to the measured ones.

Verification column base for SHS 160

- In following example, the column from square hollow section SHS 150x16 is connected to concrete block with the area dimensions $a' = \ 750\ \mathrm{mm}$, $b' = 750\ \mathrm{mm}$ and height $h = 800\ \mathrm{mm}$ from concrete grade C20/25 by the base plate $a = 350\ \mathrm{mm}$; $b = 350\ \mathrm{mm}$; $t = 20\ \mathrm{mm}$ from steel S420. Anchor bolts are designed 4 x M20, $A_s = 245\ \mathrm{mm}^2$ with head diameter $a = 60$ mm from steel 8.8 with offset at top 50 mm and left -20 mm. Grout has the thickness of 30 mm.





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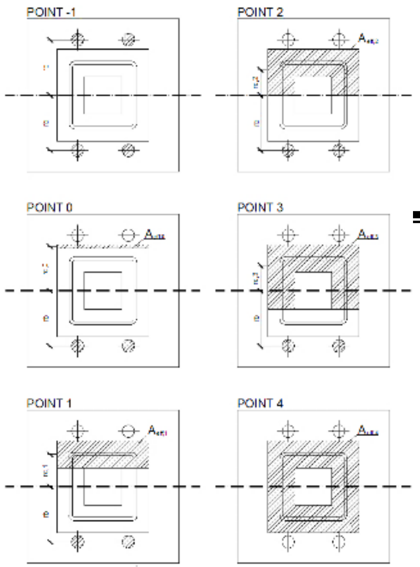
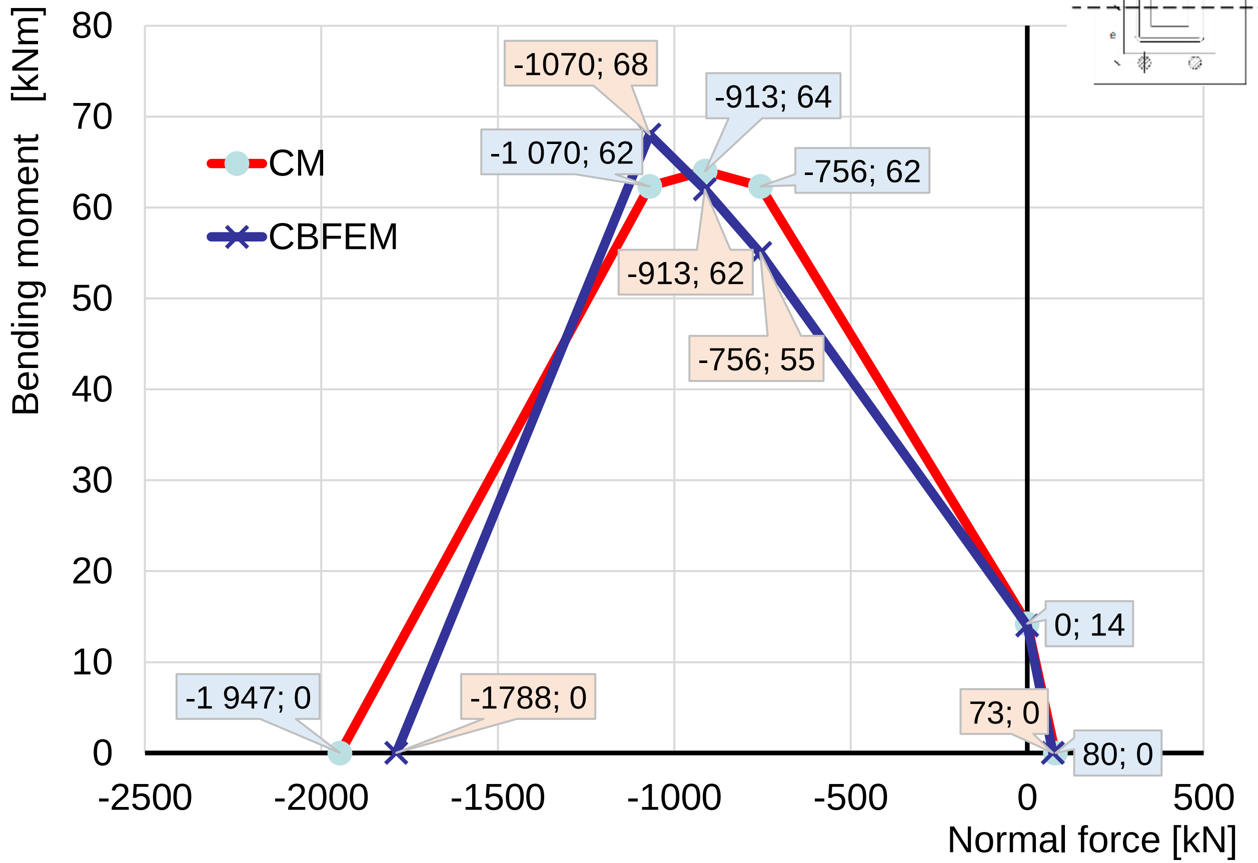
Bending moment – normal force interaction diagram



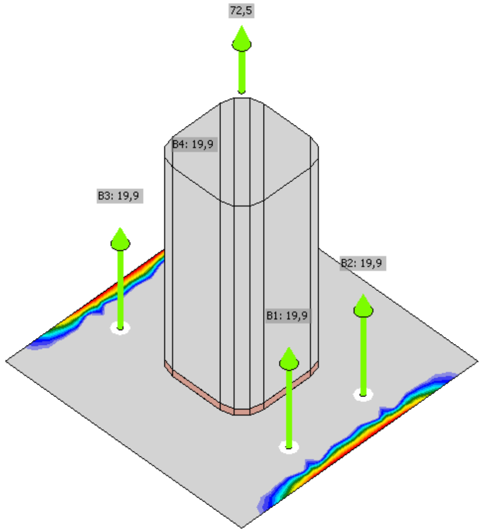
- The resistance of column base predicted by CBFEM is compared to CM on moment – normal force interaction diagram for base plate 10 mm in Figure below.

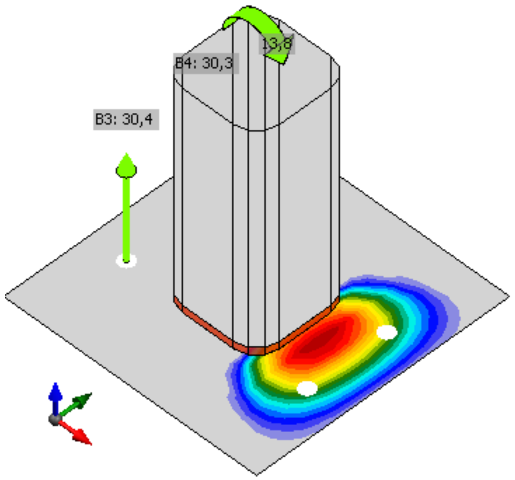


Significant points

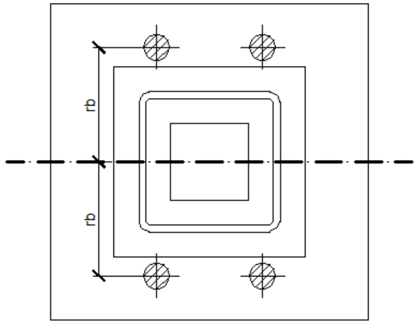
on the bending moment – normal force interaction diagram

- The equivalent stresses at the edge of the thin base plate (10 mm) loaded in pure tension show the plate contact and possible development of prying forces.

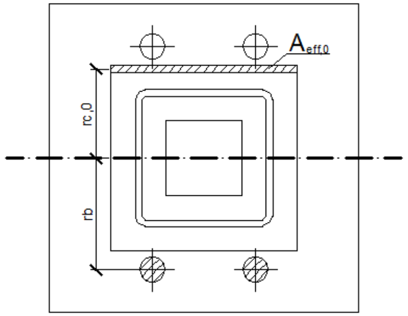


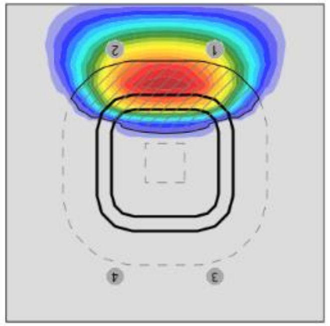


POINT -1



POINT 0





Pure tension

Pure bending

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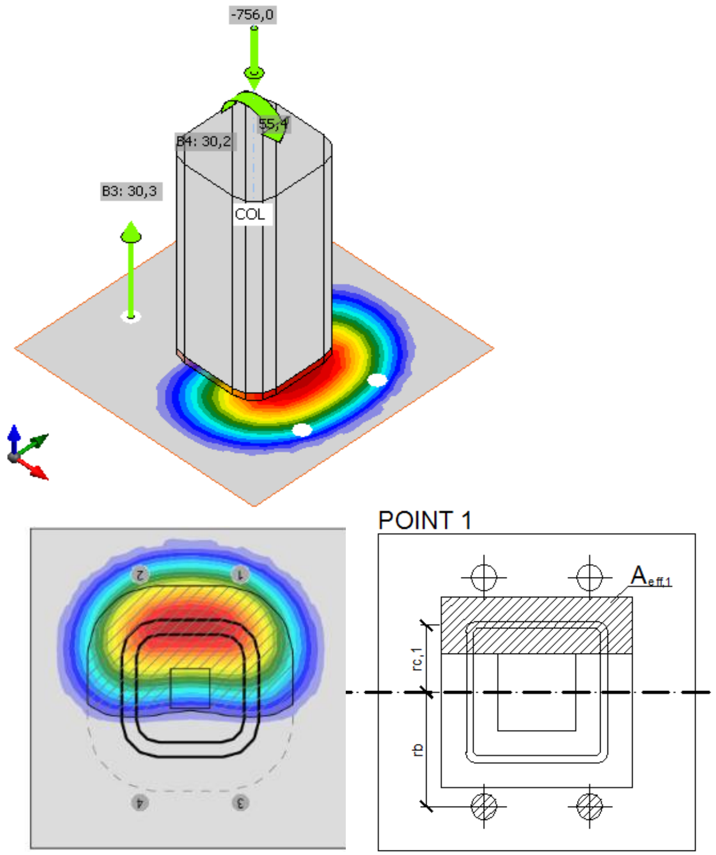
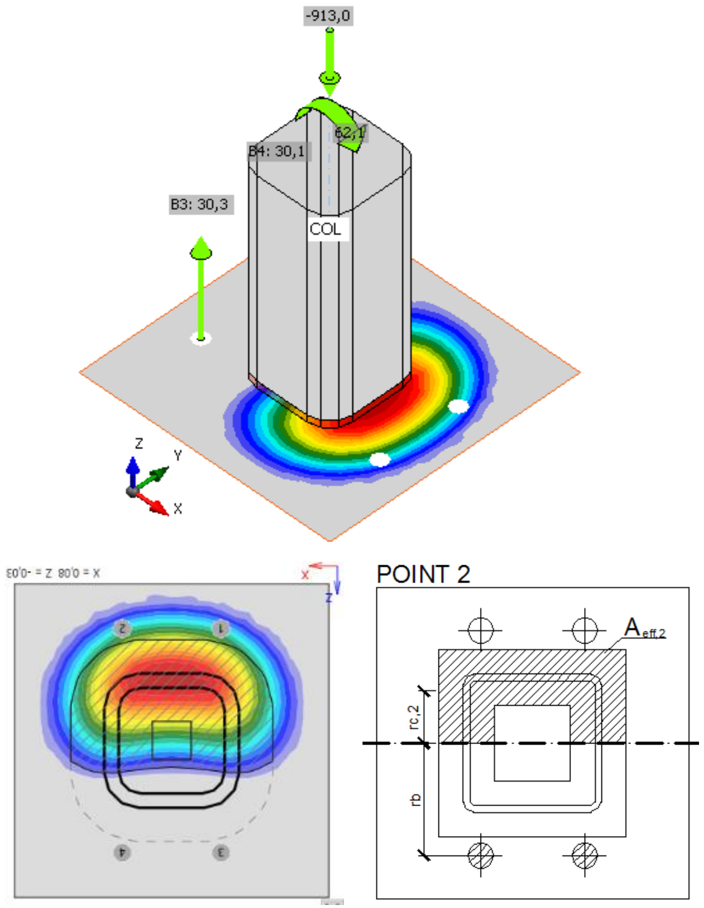
Significant points

on the bending moment – normal force interaction diagram

- The equivalent stresses and the design effective area of the contact of base plate to concrete block.



Flange in compression



Half of cross section in compression

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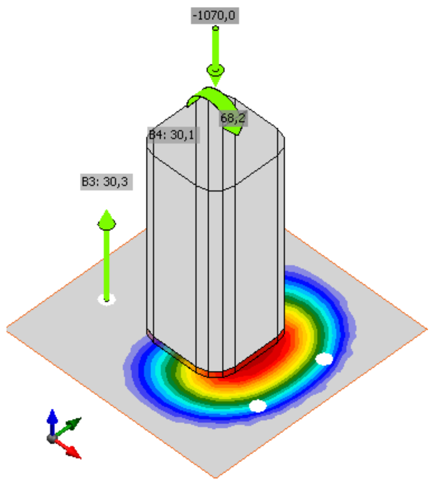
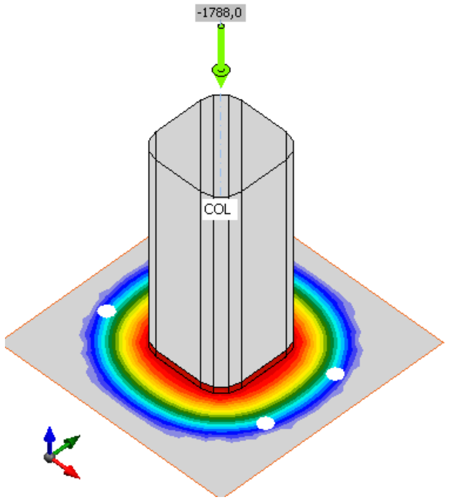
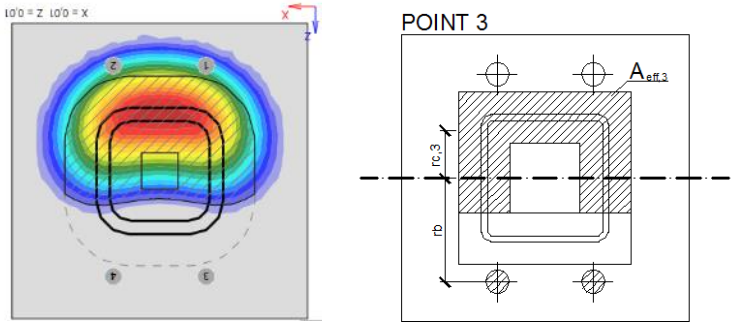
Significant points

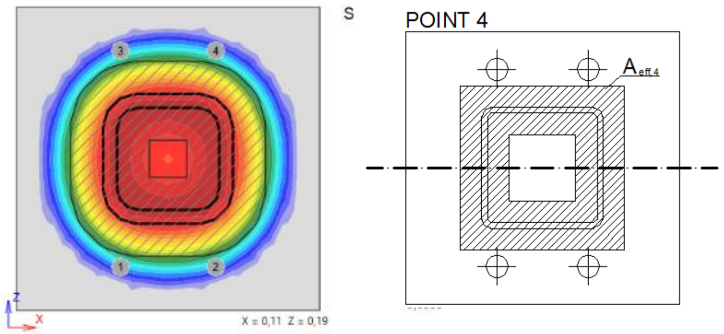
on the bending moment – normal force interaction diagram

- The equivalent stresses and the design effective area of the contact of base plate to concrete block.







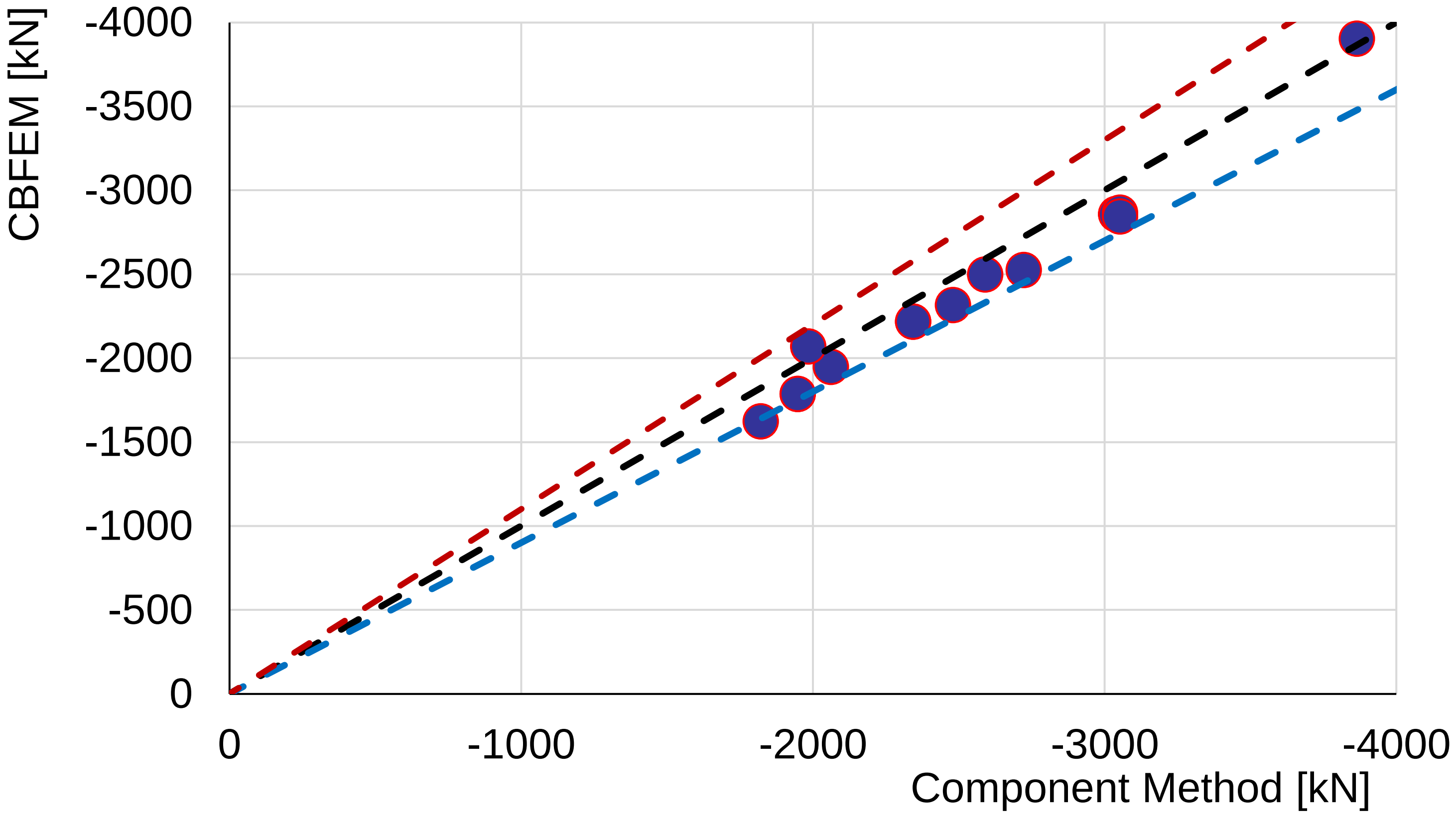


Webs in compression

Pure compresion

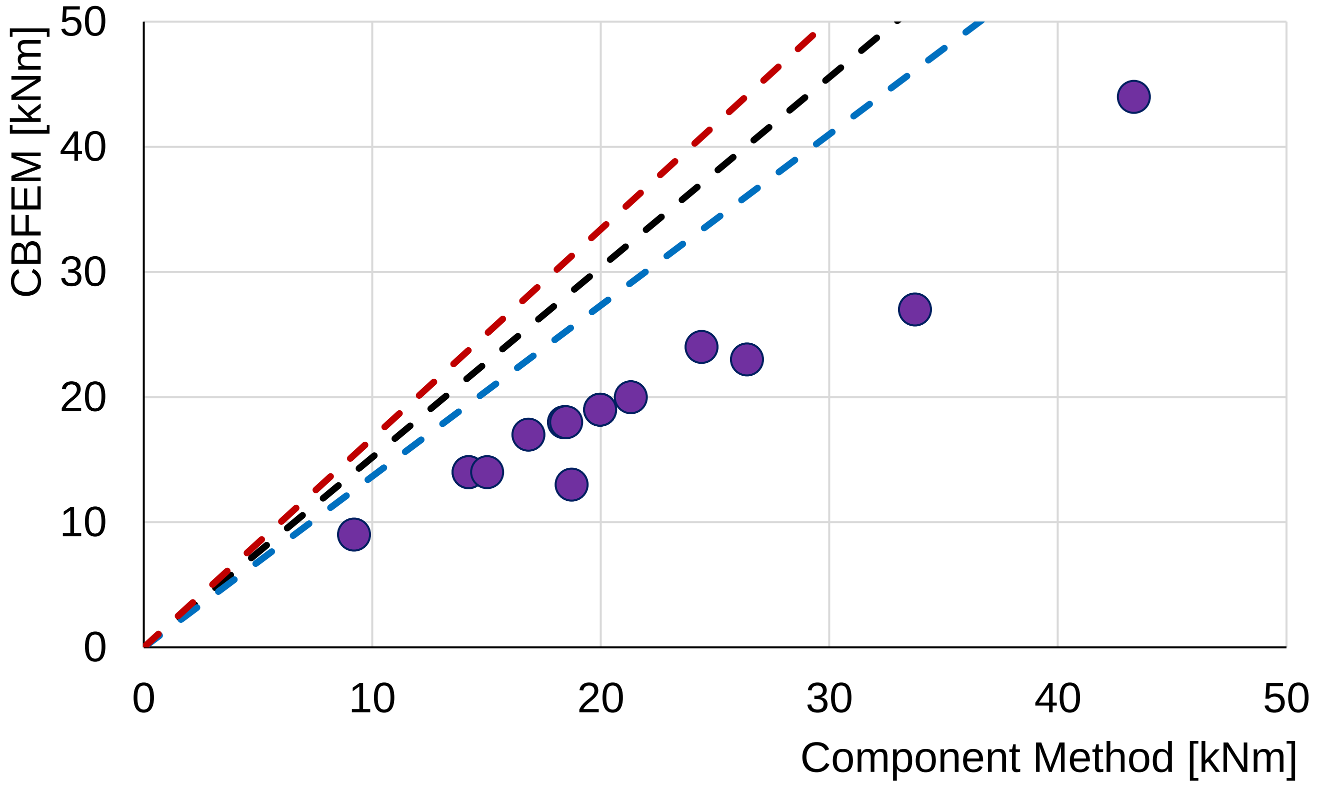
Verification for pure compression

- The resistance of column base predicted by CBFEM is compared to resistance predicted by CM in case of pure compression in Figure below.
- The graph shows similar prediction capability of both methods.



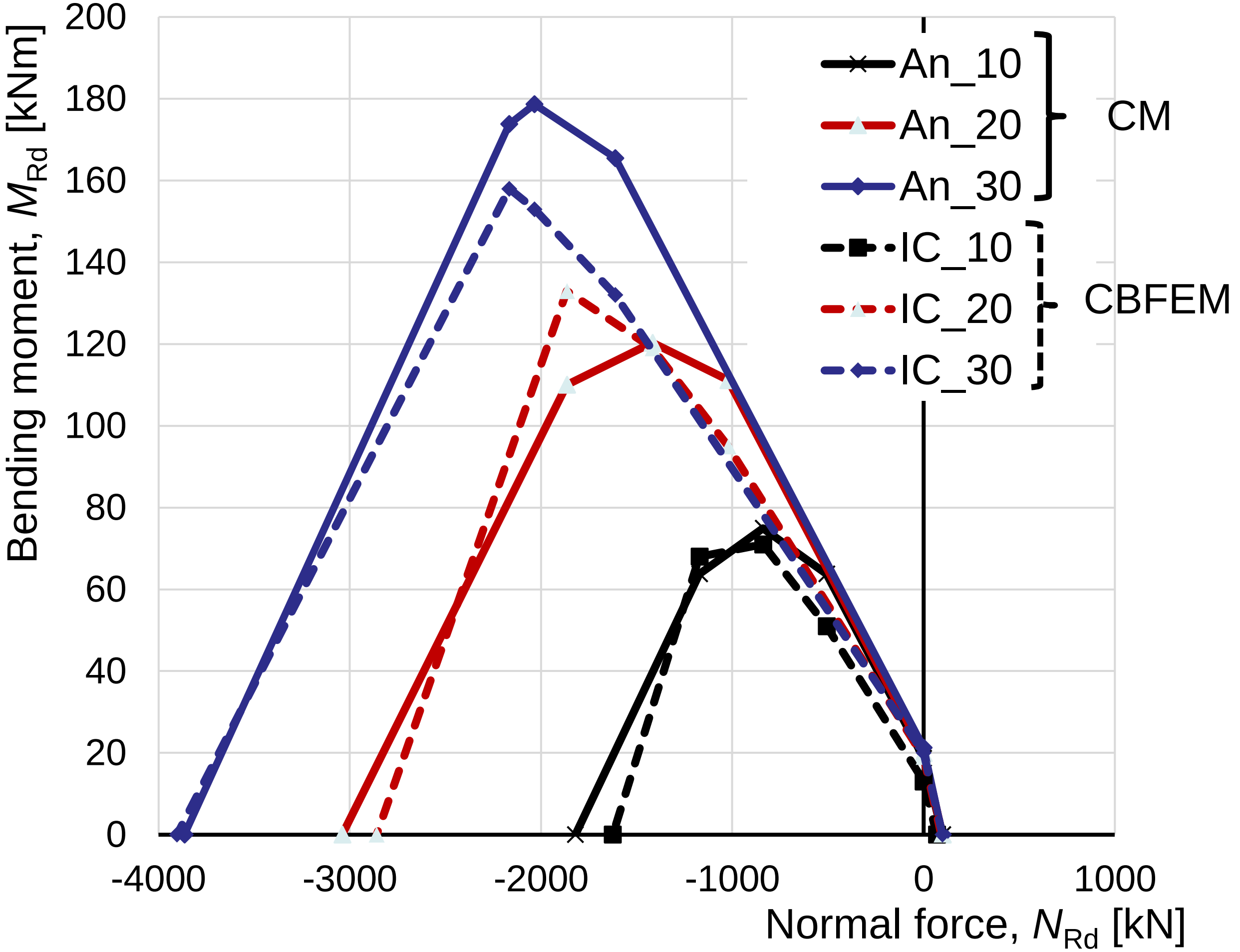
Verification for pure bending

- The resistance of column base predicted by CBFEM is compared to resistance predicted by CM in case of pure bending in Figure below.
- The graph shows similar prediction capability of both methods. CBFEM predicts a bit higher resistance due to taking into account prying forces.



Sensitivity study base plate thickness; 10; 20; 30 mm

- The resistance of column base predicted by CBFEM is compared to CM on moment – normal force interaction diagram for base plates 10 mm, 20 and 30 mm in Figure below.



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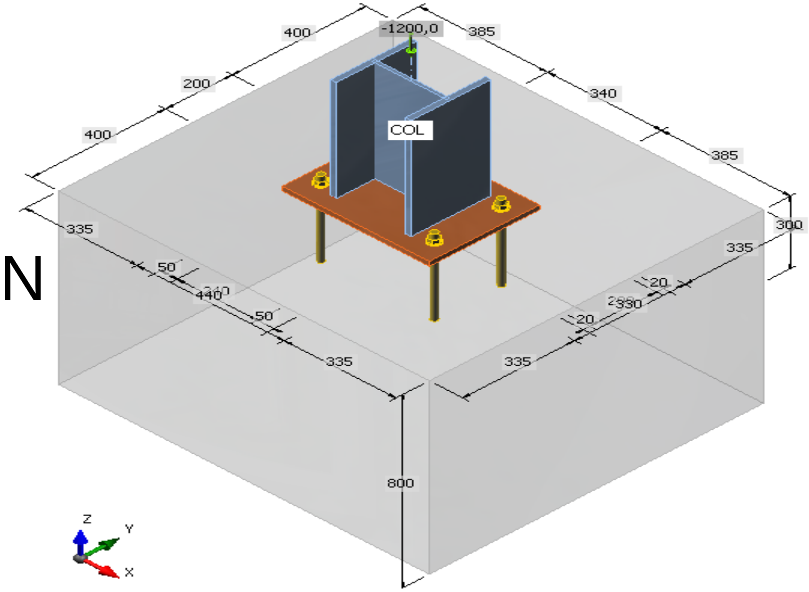
Open section column loaded in compression

Inputs

- Column, cross section HEB 240, steel S235
- Base plate, thickness 20 mm, offsets top 100 mm, left 45 mm, steel S235
- Concrete block, concrete C20/25, offset 335 mm, depth 800 mm, grout thickness 30 mm, grout quality C20/25
- Anchor bolt, M20 8.8

Output

- Axial force resistance $F_{j.Rd}$ = -1744,2 kN



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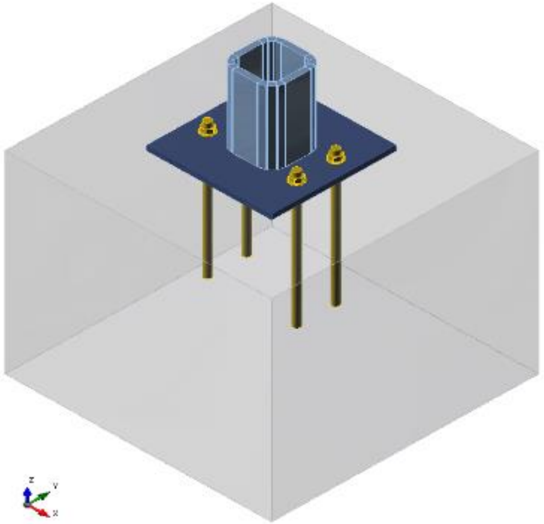
Hollow section column loaded in compression and bending

Inputs

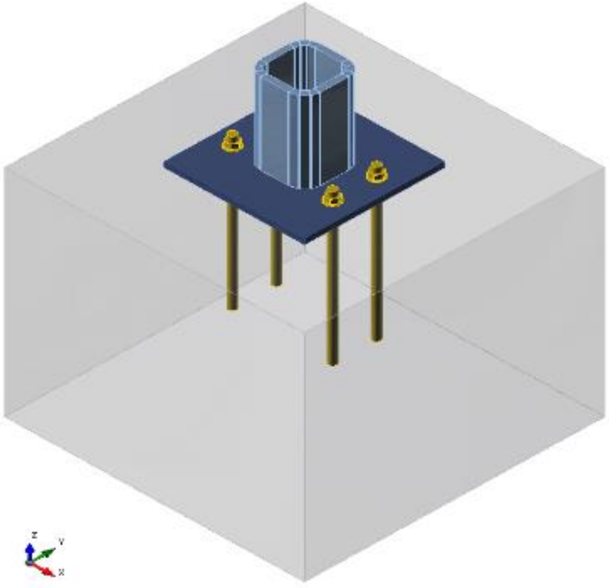
- Column cross section: SHS 150/16, steel S460
- Base plate: thickness 20 mm, offsets at top 100 mm, on left 100 mm, welds 8 mm, steel S460
- Anchor bolts: M20 8.8., anchoring length 400 mm, offsets top layers 50 mm, left layers -20 mm, shear plane in thread
- Foundation block: concrete C20/25, offset 200 mm, depth 800 mm, shear force transferred by friction
- Grout thickness 30 mm
- Loading
  - Axial force N = -913 kN
  - Bending moment M_y = 62,1 kNm



Hollow section column loaded in compression and bending

Outputs

- Plate $\varepsilon = 0{,}3\ \%$;
- Anchor bolts 99,7 % ($N_{Ed} = 30{,}3\ \mathrm{kN} \leq N_{Rd,c} = 30{,}4\ \mathrm{kN}$ (critical component concrete cone breakout)
- Welds 57,7 % ($\sigma_{Ed} = 239.9\ \mathrm{MPa} \leq \sigma_{Rd} = 416\ \mathrm{MPa}$)
- Concrete block 83,0 % ($\sigma = 33{,}4\ \mathrm{MPa} \leq f_{jd} = 40\ \mathrm{MPa}$)
- Secant rotational stiffness $S_{js} = 7{,}4\,\frac{\mathrm{MNm}}{\mathrm{rad}}$



Assessment III

- How is limited in CBFEM the resistance of base plate?
- How is modelled in CBFEM for column base design the concrete block?
- Which part under base plate is considered in roe resistance?
- How is limited the design of anchor bolts?
- What is difference between design of column base and concrete column in compression?
- What is the reason for higher resistance of column base in tension with base plate in failure mode 1-2?

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Summary

Lecture 4

Column base

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Summary

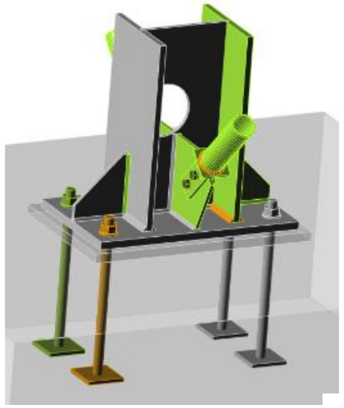
- The column bases are designed with plastic distribution of forces under the base plate.
- Concrete in compression under the base plate is designed considering its spatial stress.
- The homogeneous stress under the flexible base plate is expected for the elastically deformed base plate.
- Column bases are often subjected to the interaction of normal force and bending moment.

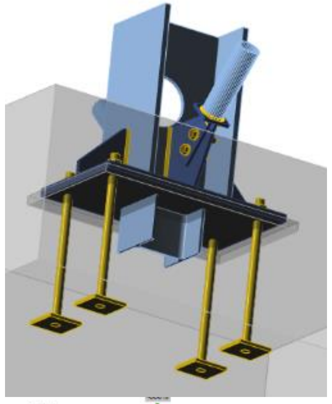
Summary

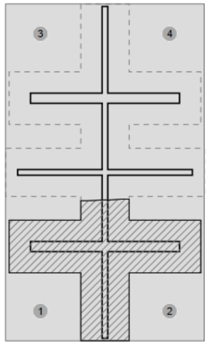
- If more rows of anchor bolts are activated, only steel failure of anchor bolts is allowed to ensure ductile failure.
- In the component method, prying of the anchor bolts is limited to failure mode 1-2.
- In CBFEM, prying forces are taken into account when determining the bearing capacity, and if the anchorage to concrete is strong enough, the predicted resistance may be higher.

What is the major reason for using CBFEM for column bases?

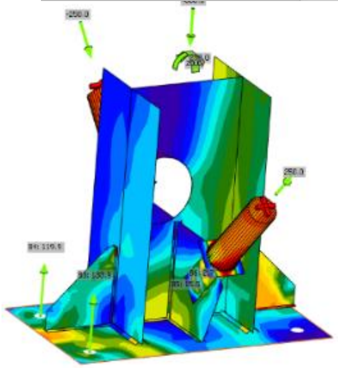
- **Generally loaded complex column base** is very difficult to design by Component Method.
- The example of design by CBFEM is shown below.



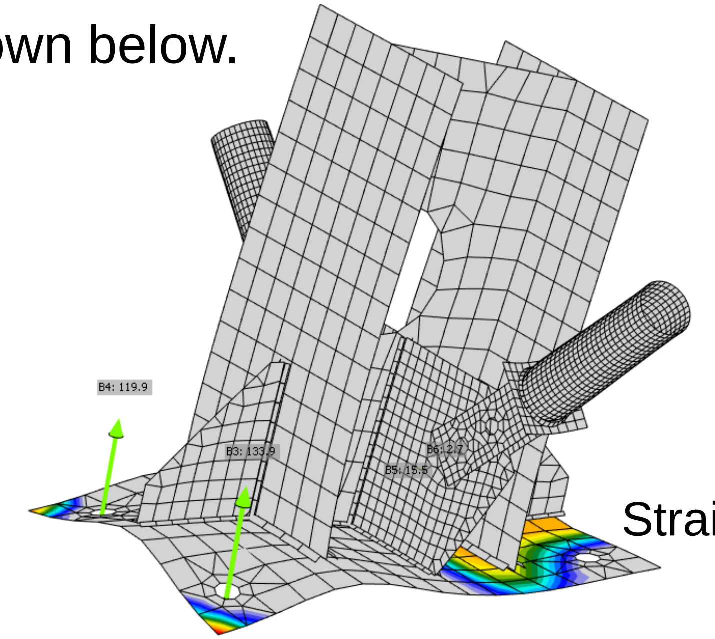




Foot print



Stress



Strain

- **Resistance limited by anchor bolt failure**
  - Strain 3,4 %
  - Prying forces are taken into account

Thank your for attention

URL: steel.fsv.cvut.cz

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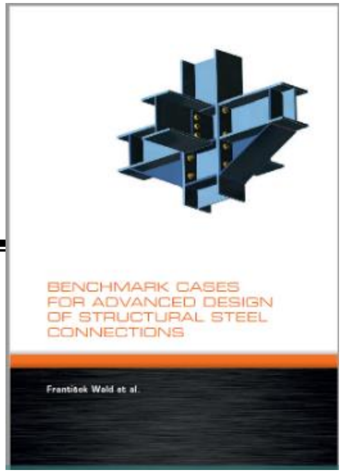
Luboš Šabatka, Jaromír Kabeláč, Drahoš Kojala

Notes to users of the lecture

- <u>Subject</u> Design of column bases of steel structures.
- <u>Lecture duration</u> 60 mins
- <u>Keywords</u> Civil Engineering, Structural design, Steel structure, Column base, Steel to concrete connection, Joint, Component Method, Component based Finite Element Method, Anchor bolts, Eurocode.
- <u>Aspects to be discussed</u> Design of anchor bolts, Reasons and methods of classification, Principles of CM, Components in column base for CM, Components in column base for CBFEM, Principles of CBFEM, Spatial stresses in concrete block, Model of stress distribution under the base plate.
- <u>Further reading</u> relevant documents in references and relevant European design standards, Eurocodes including National Annexes.
- <u>Preparation for tutorial exercise</u> see examples in References.

Sources



Bajer M., Vild M., Barnat J., Holomek J., Influence of Selected Parameters on Design Optimisation of Anchor Joint, in *Steel, Space and Composite Structures,* Singapore, 2014,149–158.

Kuhlman U., Krimpmann M., Hofmann J., Wald F., et al, *Design of steel-to-concrete joints, Design manual II*, ECCS Brussels, 2013.

Steenhuis M., Wald F., Sokol Z., Stark J.W.B., Concrete in Compression and Base Plate in Bending, *Heron*, 2008, 53, 1/2, 51-68.

Wald F. et al, *Benchmark cases for advanced design of structural steel connections*, Česká technika ČVUT, 2016.

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Wald F., Sokol Z., Steenhuis M., Jaspart, J.P., Component Method for Steel Column Bases, *Heron*, 53, 2008, 3-20.

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Standards

CEN/TR 17081:2018 Design of fastenings for use in concrete - *Plastic design of fastenings with headed and post-installed fasteners*, CEN, Brussels, 2018, ready for release.

EN1992-1-1:2006, Eurocode 2, Design of concrete structures, Part 1-1, *General rules and rules for buildings,* CEN, Brussels, 2006.

EN1992-4:2018 Eurocode 2, Design of concrete structures – Part 4: Design of fastenings for use in concrete , CEN, Brussels, 2018, ready for release.

EN1993-1-8:2006, Eurocode 3, Design of steel structures, Part 1-8, *Design of joints*, CEN, Brussels, 2006.

EN1994-1-1:2010, Eurocode 4, Design of composite steel and concrete structures, Part 1-1, *General rules and rules for buildings*, CEN, 2010.

ETAG 001: 2010, *Guideline for European Technical Approval of Metal Anchors for Use in Concrete – Annex C: Design Methods for Anchorages,* Brussels, EOTA, 2010.

The standards related to anchor bolts

- Till the end of last century were anchor bolts designed according to experimental results summarised in design tables.
- Majority or current standards for anchorages to concrete are based on failure mode method, Concrete capacity design method, developed by prof. R. Eligehausen and his students at University of Stuttgart, see Eligehausen R., Mallée R., Silva J. F., Anchorage in concrete construction, Ernst & Sohn, 2006.
- Currently is used in Europe for design Annex C in ETAG 001:2010 Metal anchors for use in concrete, https://www.eota.eu/en-GB/content/etags-used-as-ead/26/.
- Prestandard prEN 1992-4 was published in 2010 and valid for three years. In 2018 is expected to be published EN 1992-4:2018, which will replace Annex C in ETAG 001.
- American and Canadian standards are nearly identical. American standard ACI 318 used to contain anchorage design in Annex D. In the version from the year 2014 is described in Ch.17. Canadian standard A23.3 contains anchorage design in Annex D.
- Australian standard SA TS 101:2015 is fully compatible with ETAG, http://www.aefac.org.au.