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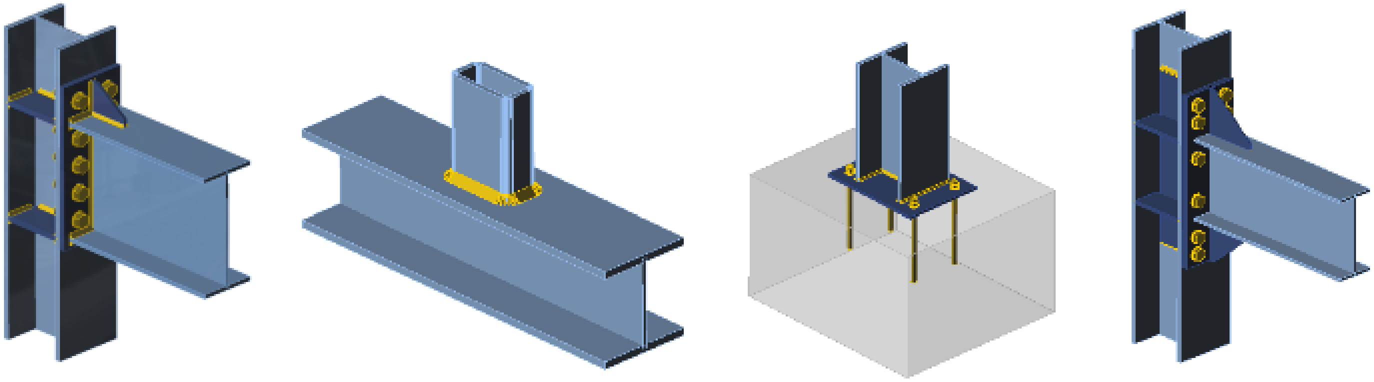
Connection design by Component Based Finite Element Method

Lecture 1
Beam to Column Moment Connection

List of lectures

1) **Beam to column moment connection**
2) Joint of hollow to open section
3) Column base
4) Seismically qualified joints



Aims and objectives

- Provide information on joint modelling
- Introduce principles of CBFEM
- Provide an online training
  to students and engineers
- Illustrate differences
  between research and design oriented FEM
- Show the process of Validation & Verification
- Offer list of references relevant to the topic

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Beam to column moment connection

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Tutorial

- This lecture describes principles of **FEA modelling** of beam to column moment connection.
- Survey of both simple and FEM analyses and modelling are shown.
- Finally Validation, Verification and Benchmark case is presented.

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Outline of the lecture

- **Introduction to design**
  - Design models
  - Global analyses
  - Classification
  - Component method
  - Interaction of internal forces
  - Assessment I
- **Component Based Finite Element Method**
  - General
  - Validation
  - Verification
  - Benchmark case
  - Assessment II
- **Summary**

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Introduction to design

Lecture 1

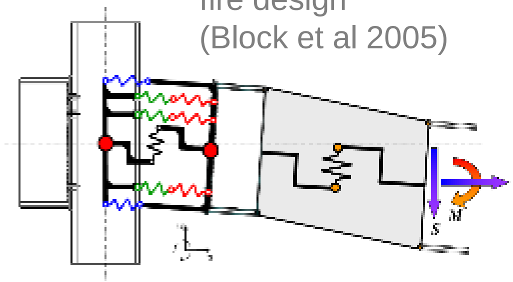
Beam to column moment connection

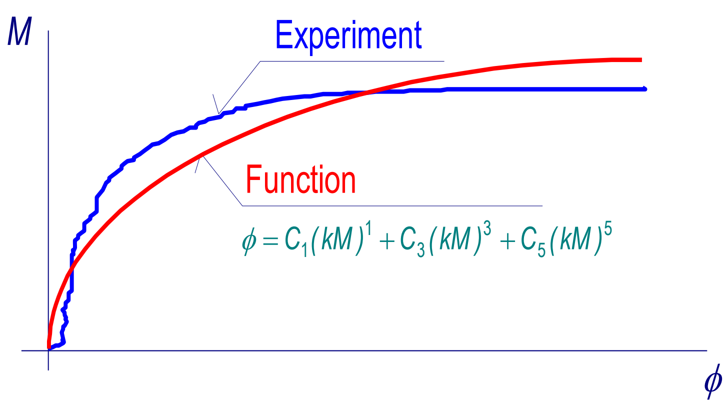
Past and Present design models

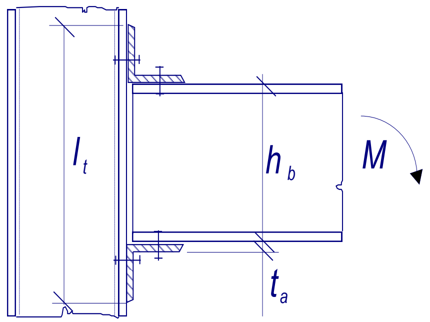
For joint design are available models:

- Experimental - history and contemporary design
- Curve fitting – currently hollow section joints design
- Analytical models
  - **Component Method (CM)**
- Research oriented finite element method
- Design oriented finite element method
  - **Component based FE Method (CBFEM)**

An example of component model for fire design (Block et al 2005)



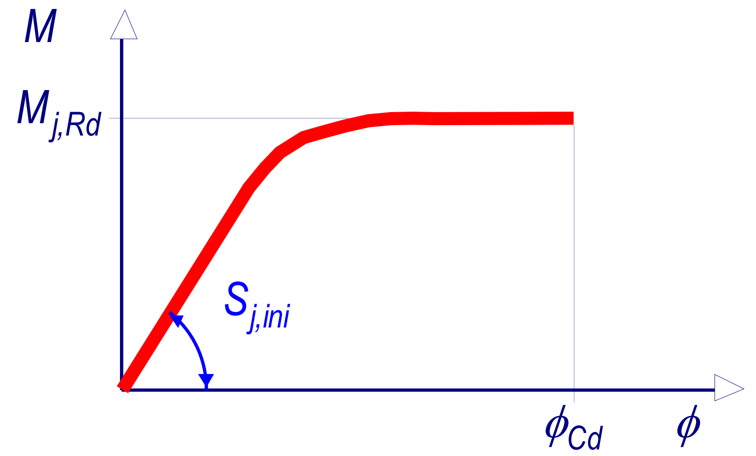




An example of curve fitting model, Kishi and Chen (1990)

Joints characteristics in bending

- Major characteristics for joint in bending are
  - **Initial stiffness** $S_{j,ini}$
    - Small influence to distribution of internal forces
  - **Design resistance** $M_{j,Rd}$
    - Direct influence to resistance
  - **Deformation capacity** φ_{Cd}
    - Influence to plastic and seismic design only



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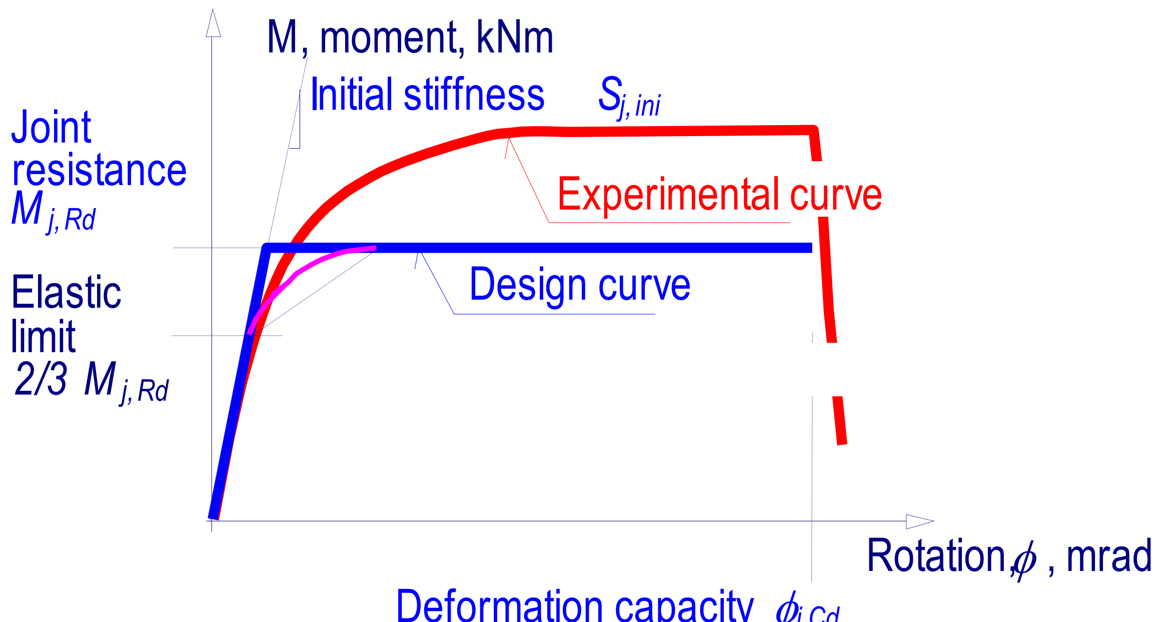
Design model and experimental behaviour

- The design model reflects the need of designers to safe prediction of joint behaviour
- As structural elements are in joint designed for its material yielding f_y or its ultimate stress f_u
- The experimentally reached resistance is never the asked design resistance



Joints deformability/stiffness

- Joint deforms due to
  - **Shear force**
    - No influence to global distribution of internal forces
    - Is closed during erection
  - **Normal force**
    - No influence to global distribution of internal forces
    - Exception in space structures of course
  - **Bending moment**
    - Significant influence to distribution of internal forces
    - The highest is in rectangular closed frames

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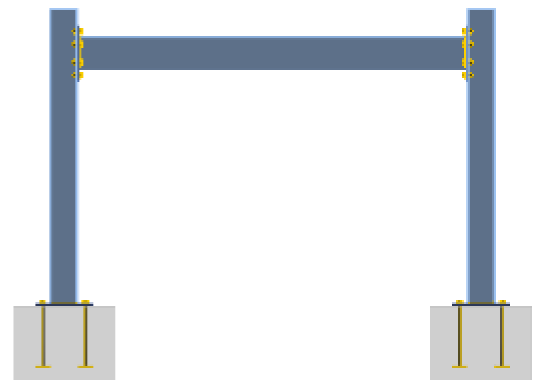
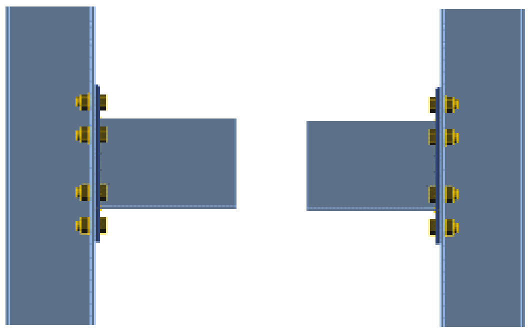
Joints in global analyses

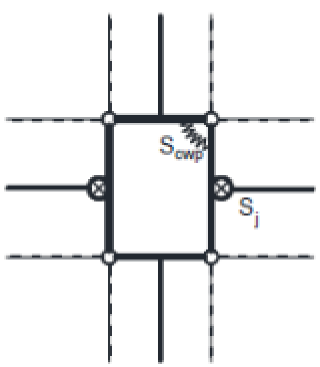
- Example of frame with its joints



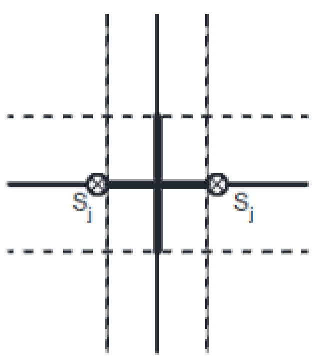


- If part of joint is flexible is in global analyses modelled as

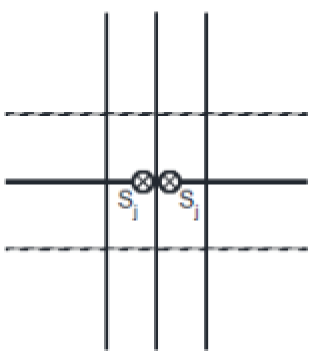
Flexible column web panel and semi-rigid connections



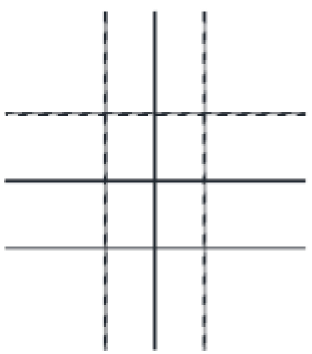
Stiff column web panel and semi-rigid or pinned connections



Stiff column web panel and semi-rigid or pinned connections

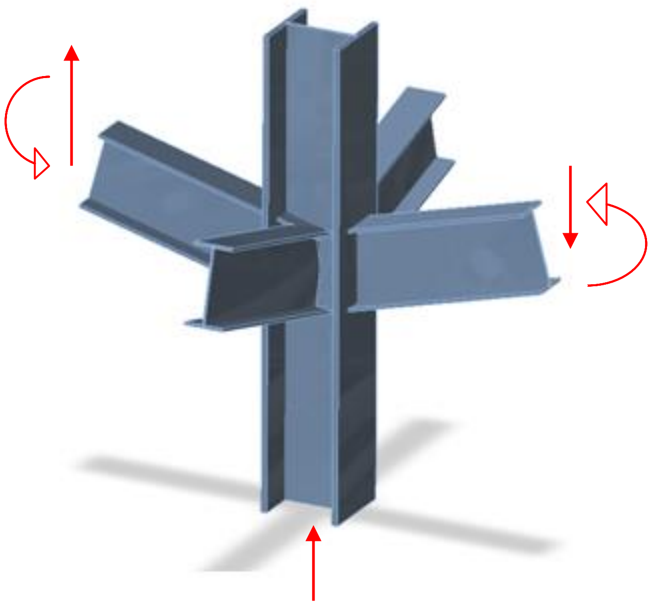


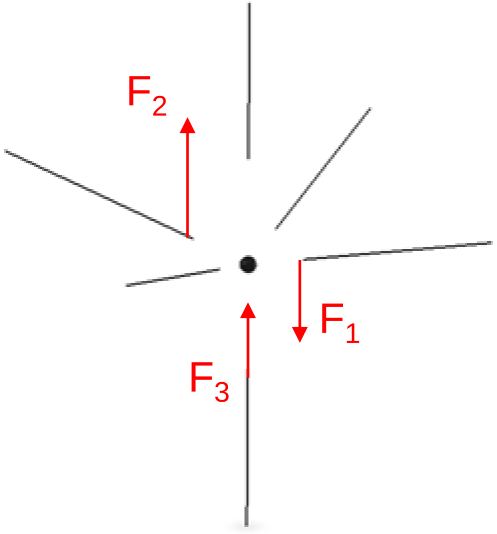
Stiff column web panel and rigid connections



Physical and theoretical joint

- In global analyses with 1D members are forces transferred to beam ends.
- Forces are kept and moments are modified by action of forces on actual arms.
- Theoretical joint should be in equilibrium, see example right below.





$$F_1 + F_2 + F_3 = 0$$

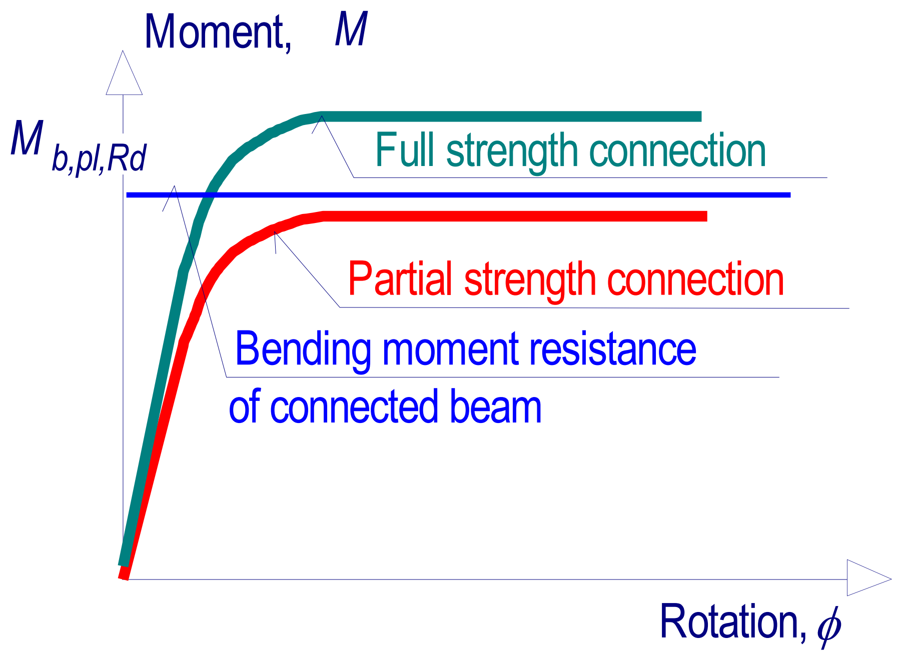
Classification

- For global analyses of steel frames are joints classified to simplify the modelling.
  (Preferable as pinned and rigid joints.)

- According to Ch. 5 in EN1993-1-8:2006
  are joints classified based on
  - Best engineering practice
  - Simplified assumption of frame behaviour
  - Actual influence of particular joint to frame design.
    (This implicates recalculation.)

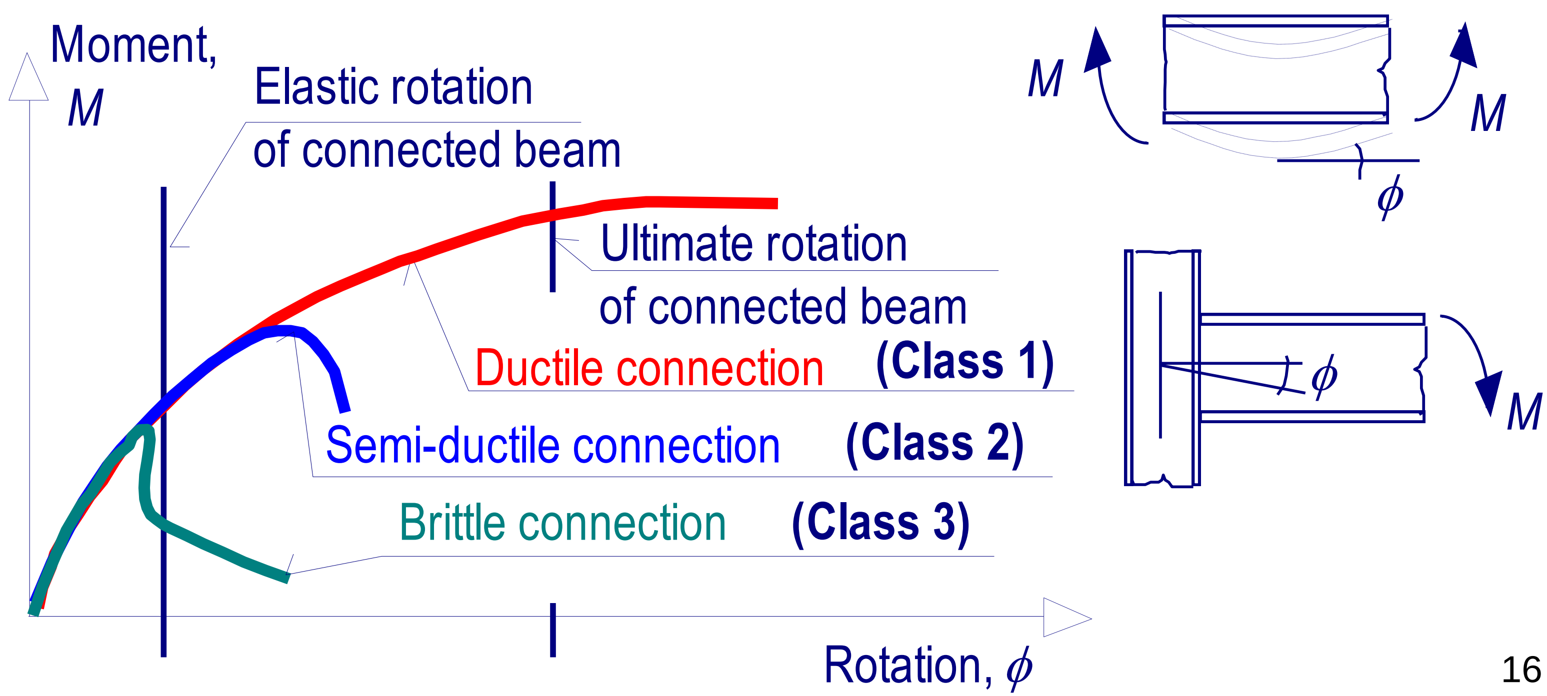
Classification based on resistance

- Bending moment resistance of connection to bending moment resistance of connected beam is compared in connections loaded in bending.
  - Full strength joints/connections $M_{j,Rd} > M_{b,pl,Rd}$
  - Partial strength joints/connections $M_{j,Rd} < M_{b,pl,Rd}$



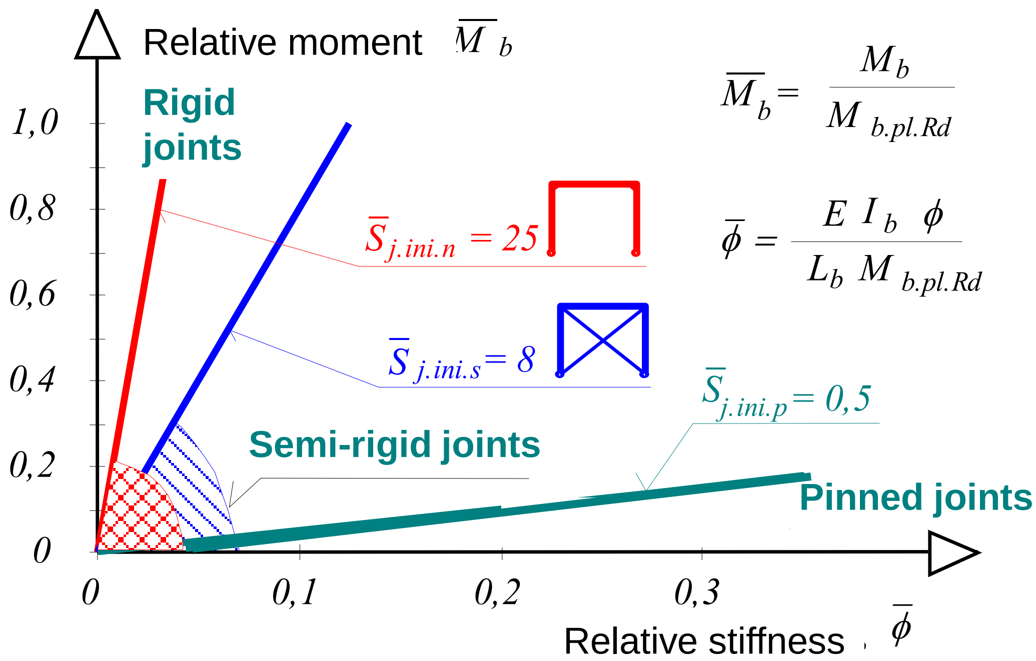
Classification based on rotational capacity

- Rotational capacity of connection to rotational capacity of connected beam is compared in connections loaded in bending.
  - Ductile connection
  - Semi-ductile connection
  - Brittle connection



Classification based on stiffness

- Bending stiffness of connection to bending stiffness of connected beam is compared in connections loaded in bending.
  - Rigid joint $S_{j,ini} \geq 25\ E\ I_b\ /\ L_b$ (for frames without bracing)
  - Semi-rigid joint $S_{j,ini,rigid} \leq S_{j,ini} \geq S_{j,ini,pinned}$
  - Nominally pinned joint $S_{j,ini} \leq 0{,}5\ E\ I_b\ /\ L_b$



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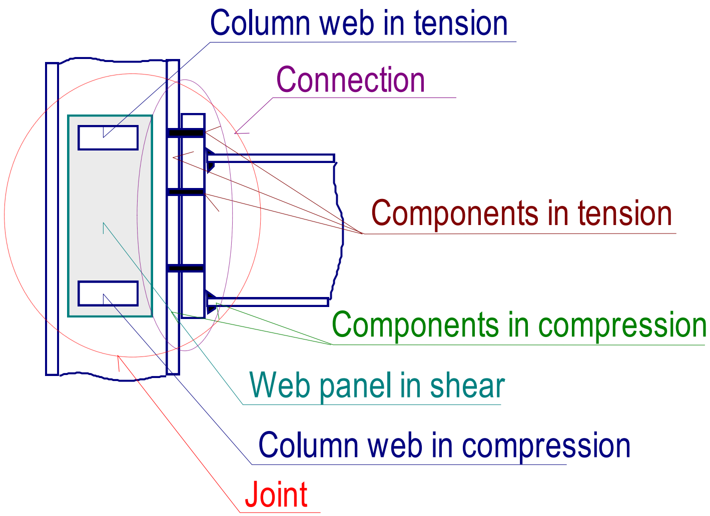
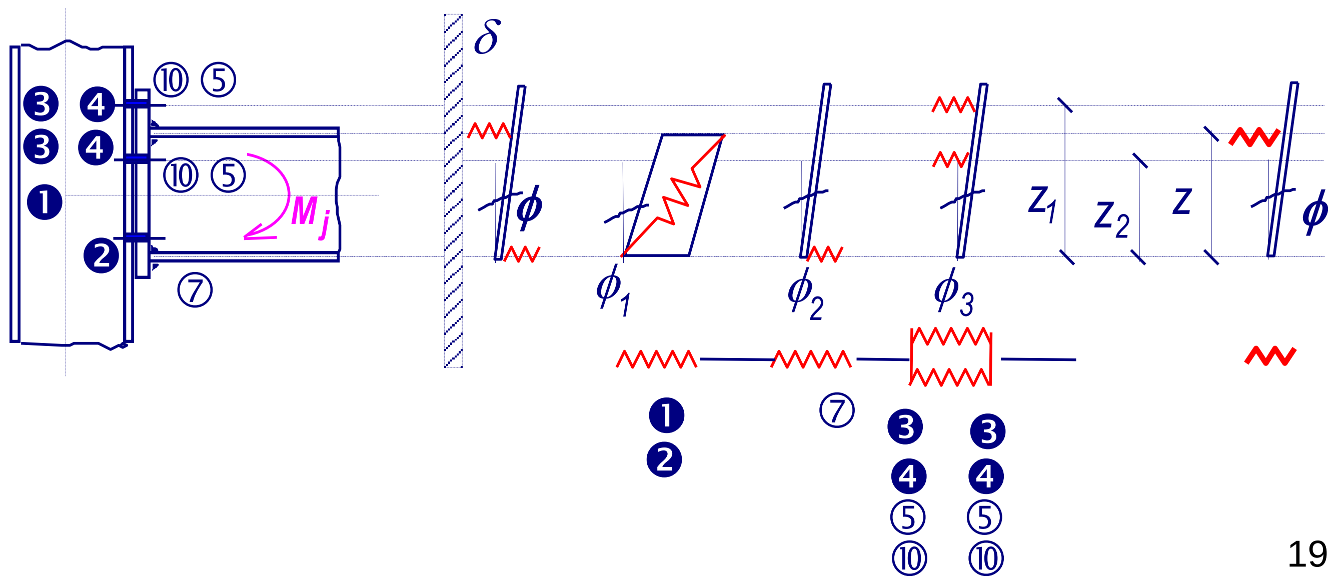
Component Method

- Component method is analytical procedure to evaluate joint resistance and stiffness. It consist of steps:
  1) **Decomposition of joint** to individual components based on assumed distribution of internal forces.
  2) **Component description** in terms of deformational stiffness and resistance.
  3) **Joint behaviour assembly** from the behaviour of its components based on assumed distribution of internal forces.



1) Decomposition of joint

- In simplified procedures are joints design in one plane
- Joint is decomposet to component based on best engineering practice
- Example below is decomposition of the beam to column joint of open I/H sections with one end plate bolted connection is
  - To components in column (❶❷❸❹), end plate connection (⑤⑩), and connected beam (⑦)
  - Finally to rigid bodyand one spring



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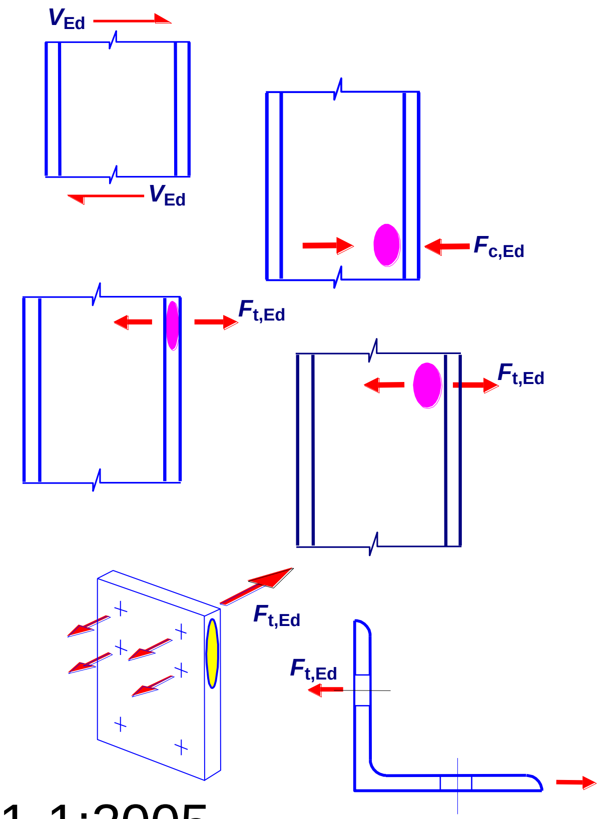
2) Component description

- The structural properties of basic joint components are described in Chapter 6 of EN 1993-1-8 for some basic components, eg. for
  - Column web panel in shear
  - Column web in transverse compression
  - Column web in transverse tension
  - Column flange in bending
  - End-plate in bending
  - Flange cleat in bending
- For composite joints are in EN1994-1-1:2005
- For another joints in literature



Introduction
- Design models
- Global analyse
- Classification
- Component meth.
- Interaction
- Assessment I

CBFEM
- General
- Validation
- Verification
- Benchmark case
- Assessment II

Summary

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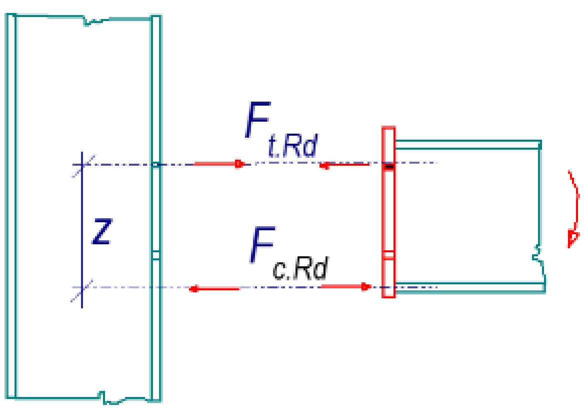
3) Joint assembly

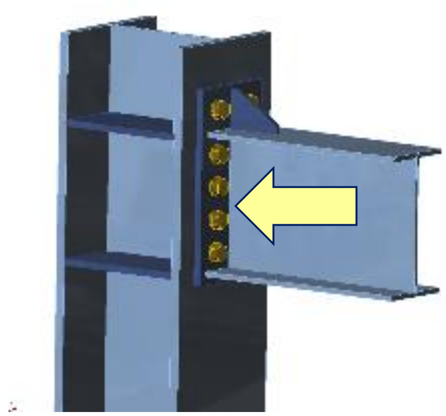
- Joint are assembled
  using the assumed lever arms of components z_x
  assumed according to best engineering practice
- E.g. for bolted connection with one bolt row
  may be guess simplified assembly
  - $F_{c,Rd}$ is compression force
    recon in the middle of bottom flange
  - $F_{t,Rd}$ is tensile force expected in the middle of bolt
  - z is estimated lever arm

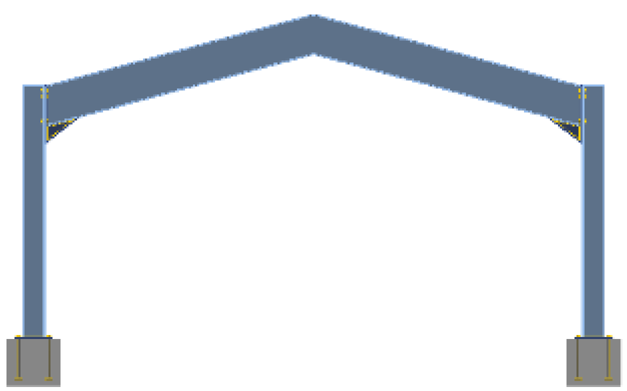


$$M_{j,Rd} = \sum_i F_{ti,Rd}\, z_i$$

Interaction
of bending moment and normal force

- Many joints are exposed to interaction of bending moment and normal forces,
- One example is simple portal frame, where the bolted eaves moment connection transmits the normal force based on the rafter inclination.
  - The Normal force may be neglectabe
    but for greater inclination is for connection significant.





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Simplified prediction of interaction of bending moment and normal force

- In EN 1993-1-8:2005 is recommended:
  - Design moment resistance of joint $M_{j,Rd}$ does not take account of any axial force N_{Ed} in the connected member. Axial force in the connected member N_{Ed} should not exceed 5% of design plastic resistance of connected element $N_{pl,Rd}$.
  - Otherwise should be considered by:
    - Linear interaction

$$\frac{N_{Ed}}{N_{j,Rd}} + \frac{M_{Ed}}{M_{j,Rd}} \leq 1$$

    - Component method
  - Interaction ratio is calculated to the vectors between points of the interaction curve.

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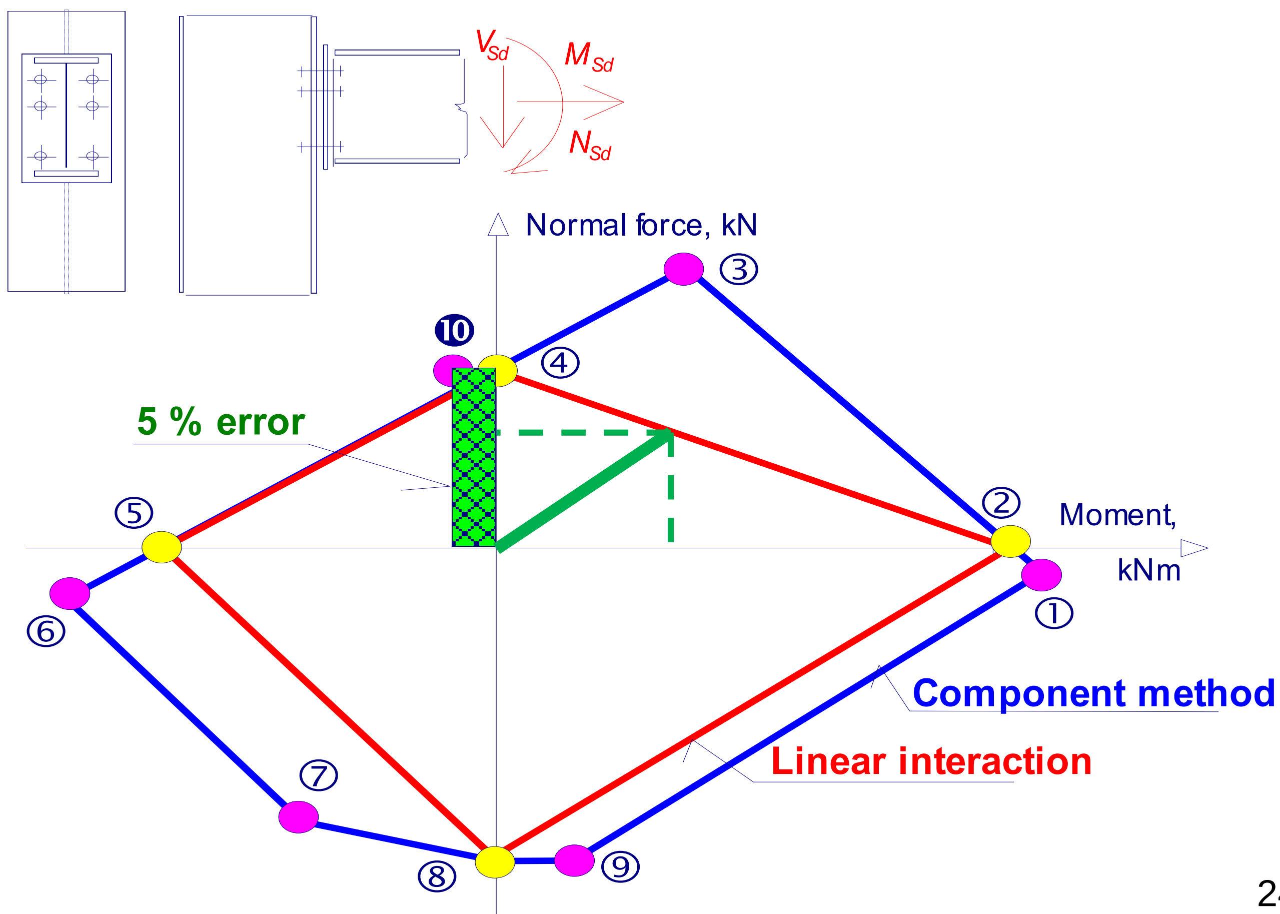
Interaction

of bending moment and normal force on beam to column joint with end plate

- The significant points are marked.
- The lines represents the limit of safe design by simple linear interaction and by component method.



Assessment I

- Describe the influence to quality of design of the three major characteristics of joint
- Principles of joint classification according to What Ch. 5 in EN1993-1-8:2006
- What's influence of joint deformation due to shear force, Normal force and bending moment
- Draw the four possible representation of joints in global analyses.
- Describe the three major steps of Component method.
- How is in Component method predicted the lever arm of internal forces?
- Describe the three major steps of Component method.
- How to predict in a simple way interaction of bending moment and normal force?

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Component Based Finite Element Method

Lecture 1

Beam to column moment connection

Material

- Bilinear ideal elastic plastic diagram is used in design oriented models as CBFEM according to Ch. 7 in EN 1993-1-5:2006 and the slope of plastic branch is due to numerical stability E/1000.
- Plastic strain in plates is limited by 5%.
- In research oriented models is calculated the true stress-strain diagram from the material properties obtained in tensile tests, which is takin into account the necking of the coupon during its yielding before rupture.

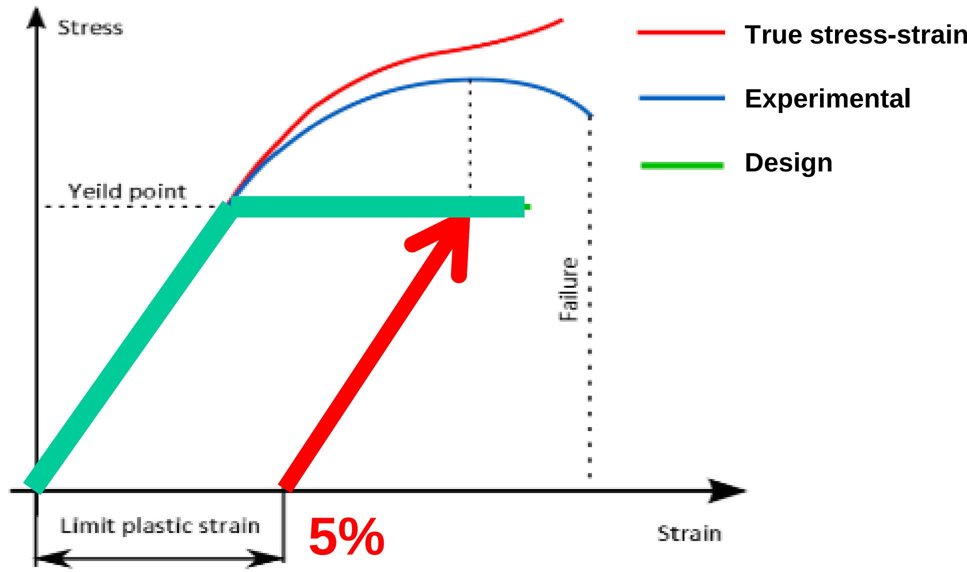

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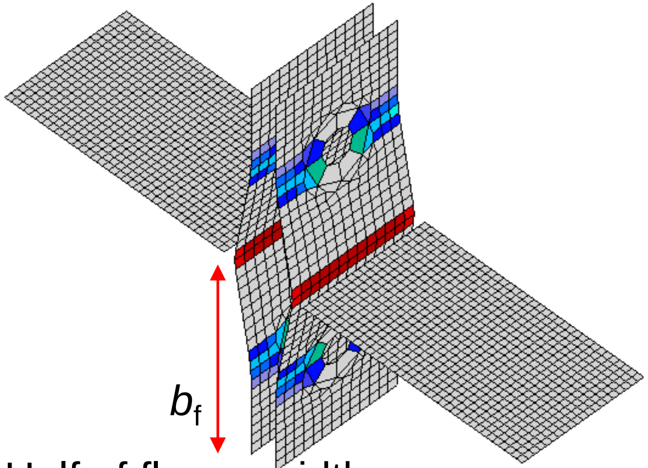
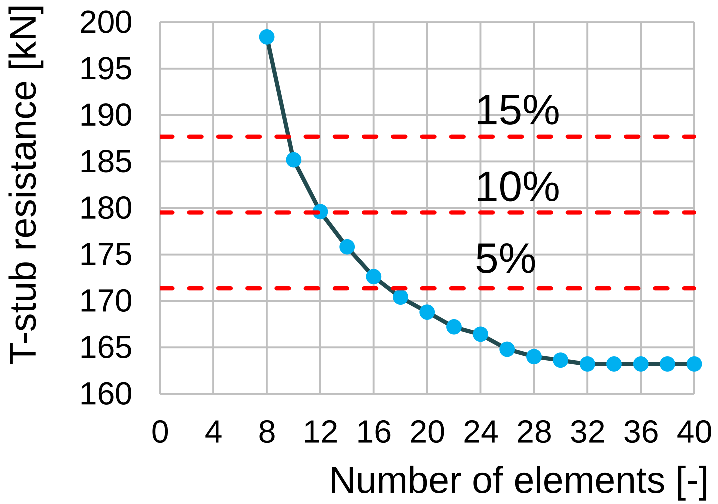
Plate

- Four node quadrangle shell elements are applied with six degrees of freedom, i.e. three translations and three rotations, in every node.
- End plates, element profiles, slender stiffener, T-stubs are modelled as plates connected in joint by constrains and the connection check is independent on the element size.
- Example of T-stub shows the influence of mesh size on the T-stub resistance.
  - Dashed lines are representing 5%, 10% and 15% difference.

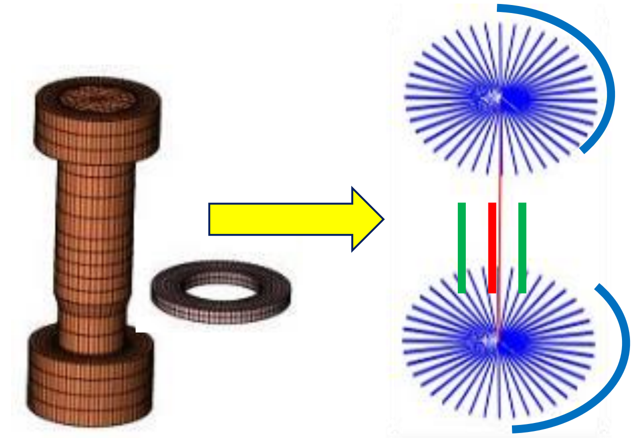


Half of flange width



Bolt

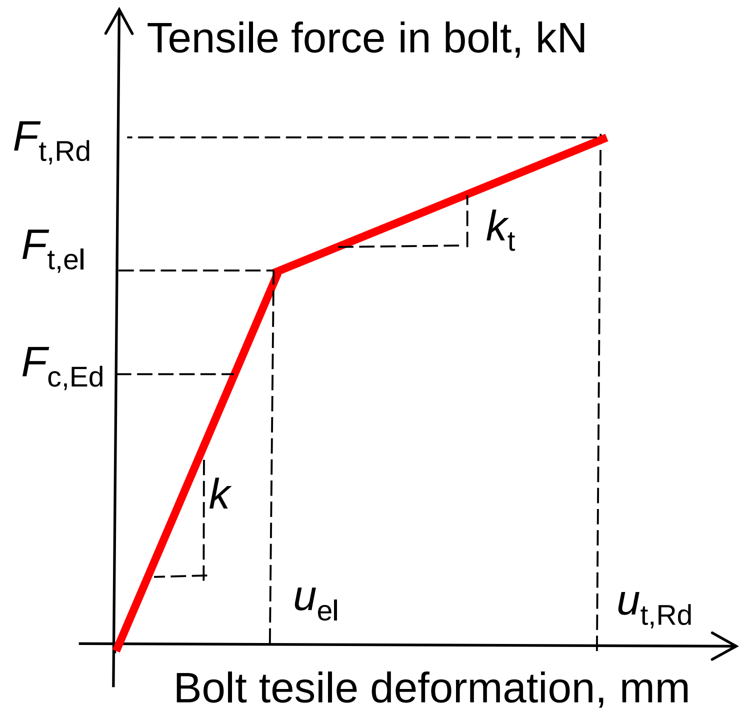
- Fan model with interpolation constrains to edges of bolt holes is used in CBFEM, but is used also in research oriented models (Bursi, Jaspart, 1998).
- Nonlinear springs are connected for
  - **Tension** in contact of
    - bolt shank and bolt head
  - **Shear** in contact between
    - plate and bolt head
    - bolt shank and plate



Fan model of bolt with constrains

Working diagram of spring model for Component bolt in tension

- For bolt´s resistance is expected maximum allowed plastic strain ε_{mpb} as 25 % of elongation to fracture of bolt according to EN ISO 898-1:2013, the values are summarised in Table below.
- The stiffness in tension is calculated as $k = E\, A_s/L_b$, where A_s is tensile area of bolt and L_b is the distance between the centers of the head and the bolt nut.



Maximum allowed plastic strains for bolts $\varepsilon_{t,Rd}$

Bolt grade	4.8	5.6	5.8	6.8	8.8	10.9
ε_{mpb} %	3,5	5,0	2,5	2,0	3,0	2,3

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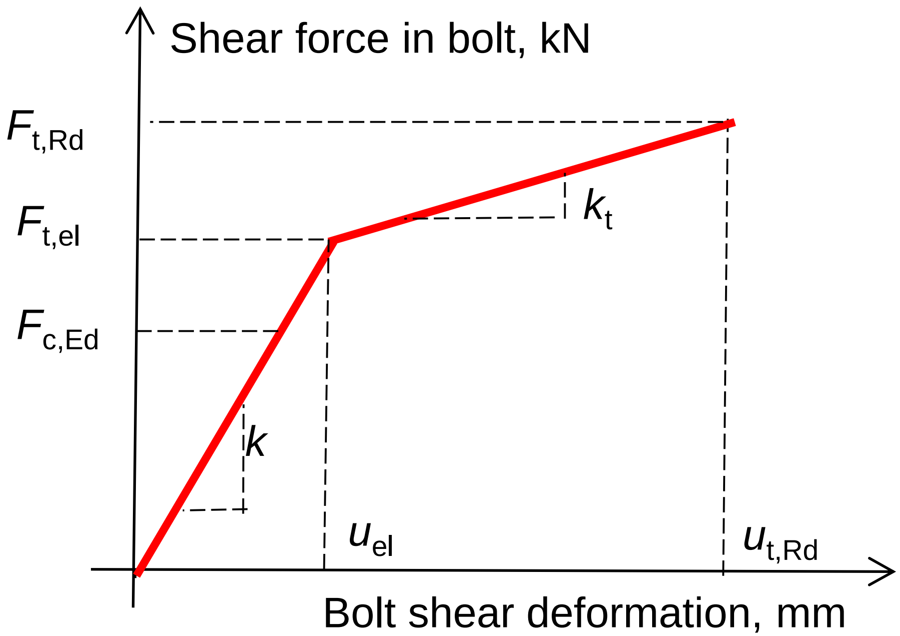
Working diagram of spring model for Component bolt in shear

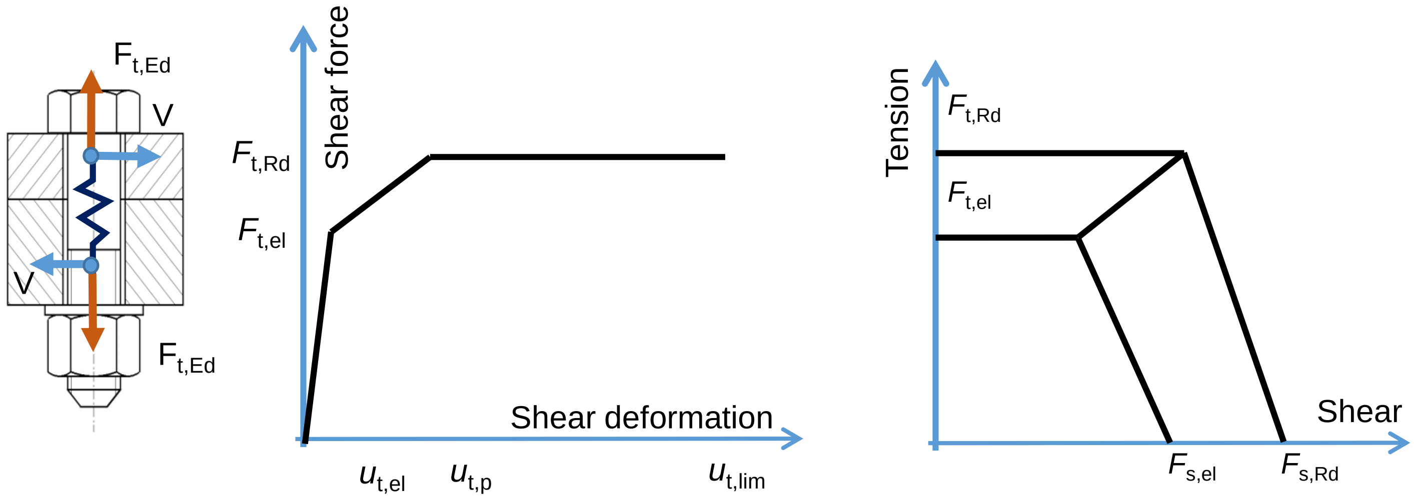
- Bolt in shear is simulated by bilinear diagram with its initial linear part and nonlinear one, which may be simplified as second linear one.
- Values are obtained by experiments and summarised in design standards.
- The values in Ch. 6 EN1993-1-8:2006 represents well the bearing of plate and bolt and shearing of the bolts shaft.



Bolt loaded in tension and shear

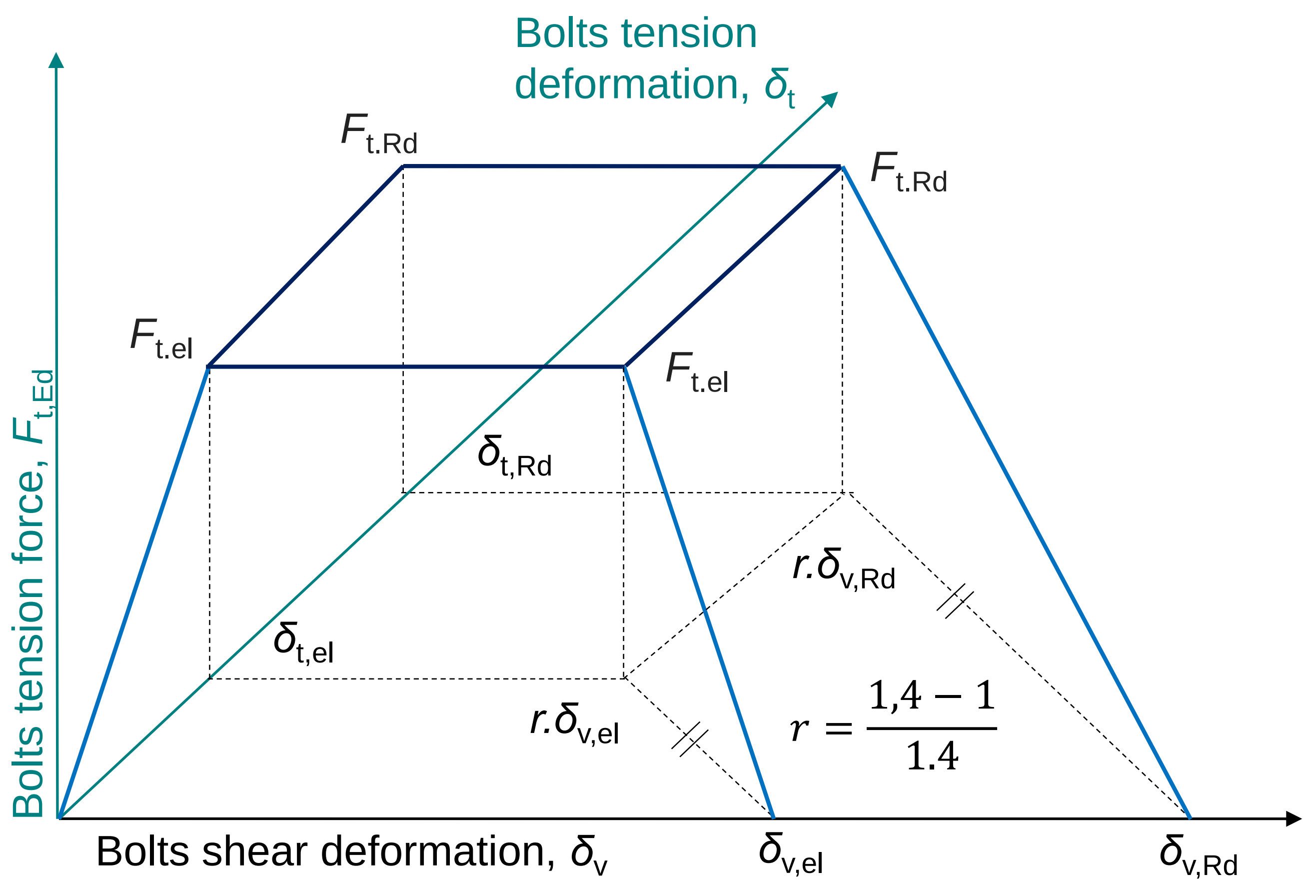
- The bolt loaded to tensile resistance $F_{t,Rd}$ has still significant shear residual resistance $F_{s,res,Rd}$.
- The interaction is described by linear/nonlinear relation, which is in CBFEM simplified for initial and second part of the curve, see Figs below

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1{,}4\ F_{t,Rd}} \leq 1{,}0$$



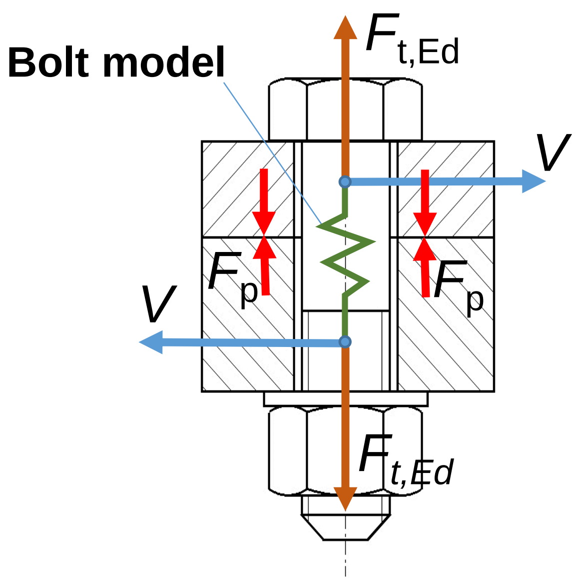
Bolts

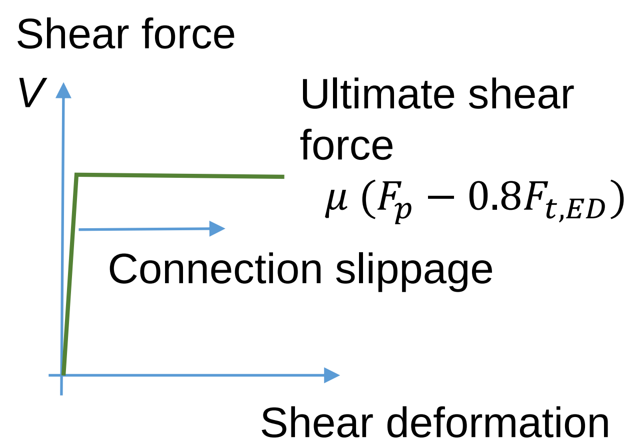
- Interaction diagram for deformation of the bolt loaded in shear and tension, (Wald et al. 2016)



Slip resistant bolt

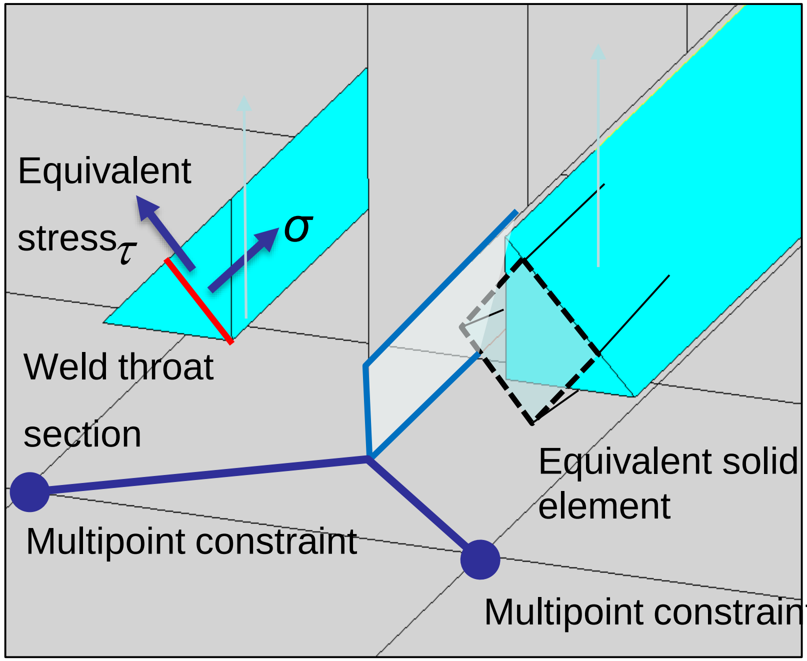
- In the preloaded slip resistant bolt is transferred the shear force by friction.
- As the friction force is reached slip resistance the shear force is transferred by bearing of the plate and shearing of bolt as regular non preloaded bolt.
- Bolt is preloaded to 70% of its strength.





Welds

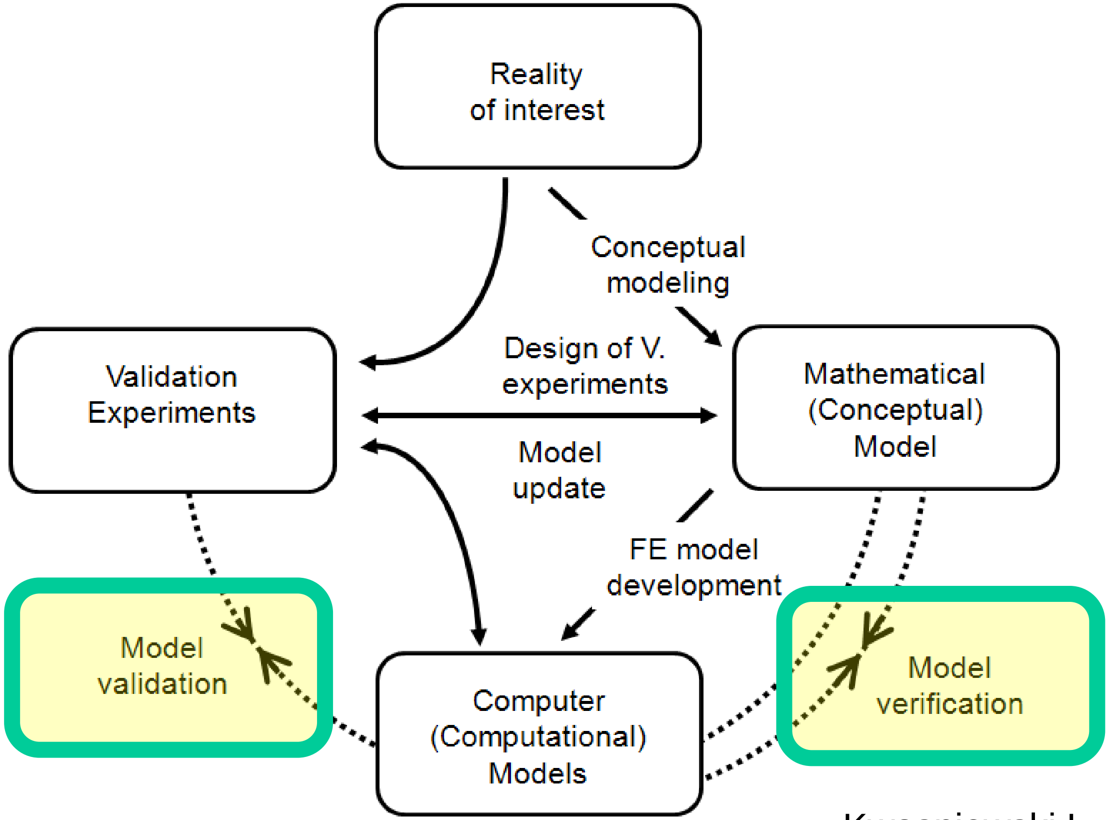
- Filled weld is modelled by equivalent solid elastoplastic element, which is added between plates to express the weld behaviour, see Fig. below.
- The element respects the weld throat thickness, position, and orientation to assure good representation of weld deformation stiffness, resistance and deformation capacity.
- The plastic strain in weld is limited to 5%.



Wald et al. (2016)

Verification & Validation

- The need and position of Verification & Validation in prediction of the reality is demonstrated on the diagram below.



Kwasniewski L. (2009)

Terminology

- **Validation**
  - compares the numerical solution with the experimental data.
- **Verification**
  - uses comparison of computational solutions with highly accurate analytical or numerical solution.
- **Benchmark case**
  - ais example for check of the software and its user by validated and simplified input and output.

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Design and research oriented model

Current approval of design models consist of

1) **Experiments**

- **Research oriented FE model** (ROFEM)

2) is **validated** on experiment.

3) Numerical experiments are prepared.

- **Design oriented analytical/numerical model** (AM/DOFEM)

4) is **verified** to numerical experiments and/or another design models.

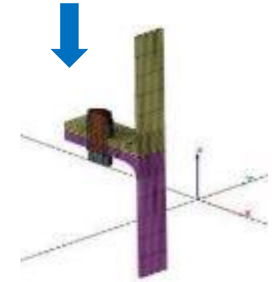
5) Sensitivity study is prepared.

6) Validity range is defined.

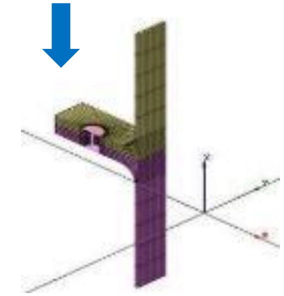
- **Benchmark case** (BC)

7) is prepared to help the users of model to check up its correctness and proper use.

Experiment



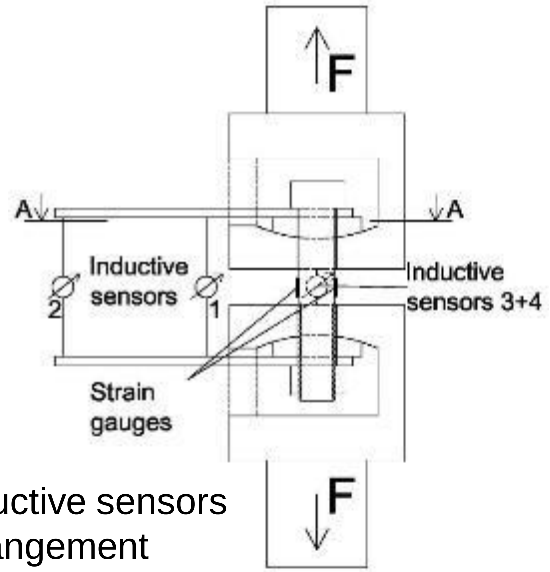
Research model



Design model

Experiments with bolts in tension

- Out of dozens of published tests, 13 bolts of different lengths and diameter were tested to obtain the detailed force-deformation behaviour.
- Bolts elongation was measured by inductive sensors.
- Bolts were fixed to the testing machine by special tools with bearing caps to ensure hinges on its ends.

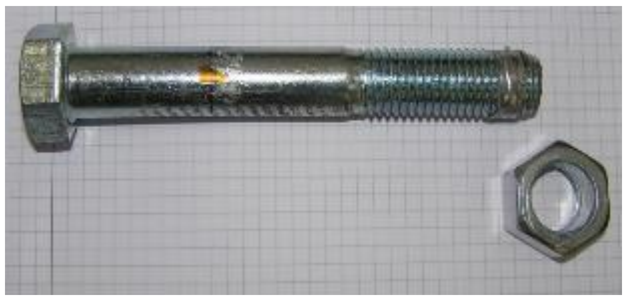


Inductive sensors arrangement

Testing machine

Failure modes of bolts in tension

- There are four possible failure modes of bolts loaded in tension:



Stripping of nut threads

Rupture of bolt close to nut

Stripping of bolt threads

Rupture of bolt close to head

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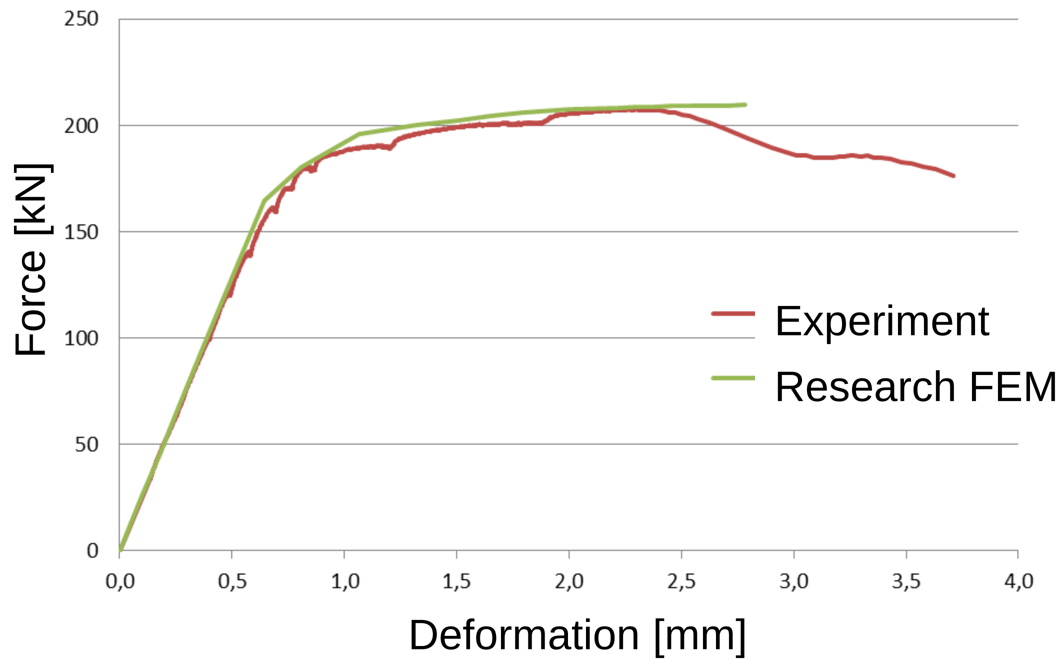
Validation for rupture of bolt close to head

- The figure shows the validation of research oriented model in case of failure mode rupture of bolt close to the bolt head.



Research oriented model of bolt

Rupture of bolt close to head

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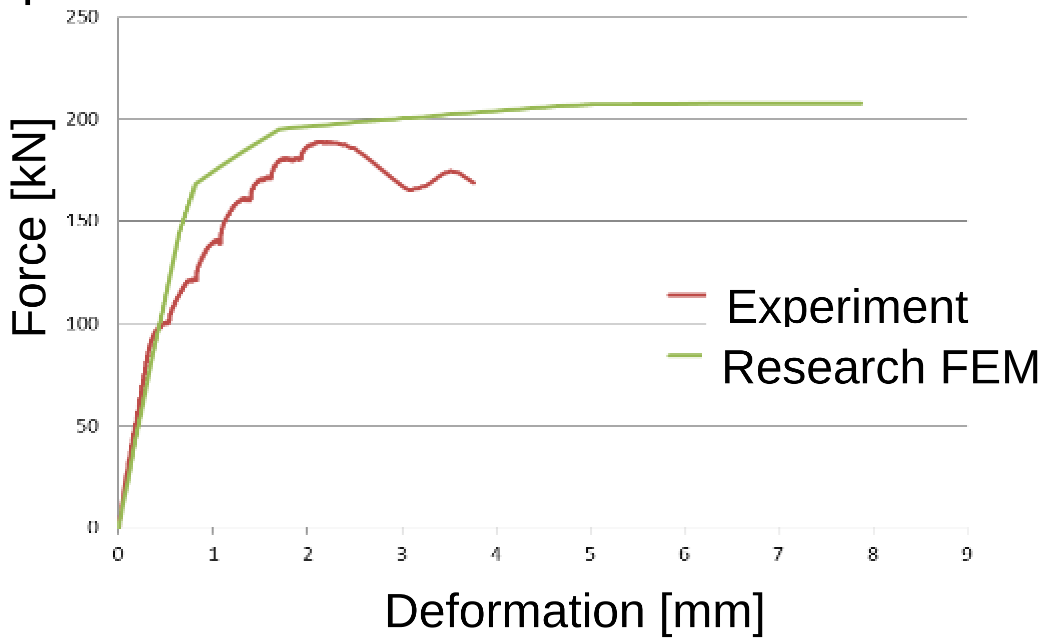
Validation of stripping of nut thread

- The validation of the research oriented model in case of failure mode stripping of the nut thread is presented below.

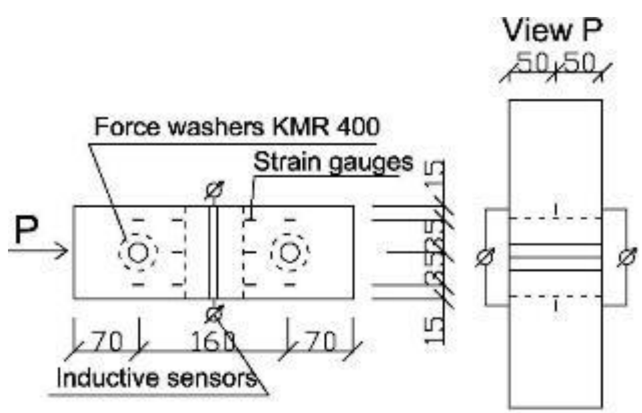


Research oriented model of bolt

Stripping of nut threads

Experiment with T-stub in tension

- Two specimens were prepared with T stubs, cross sections HEB300 and HEB400 with bolts M24 8.8.
- T-stub deformation was measured by inductive sensors.
- Strains were measured on the expected yielding lines on flanges by strain gauges.
- Forces in the bolts were measured by KMR400 rings placed under the bolt heads.

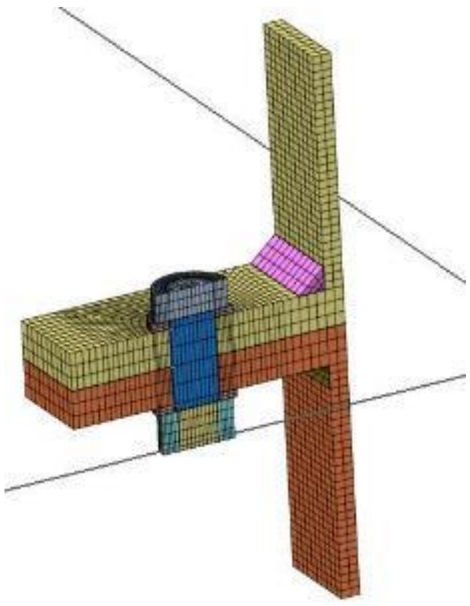


Measuring devices arrangement

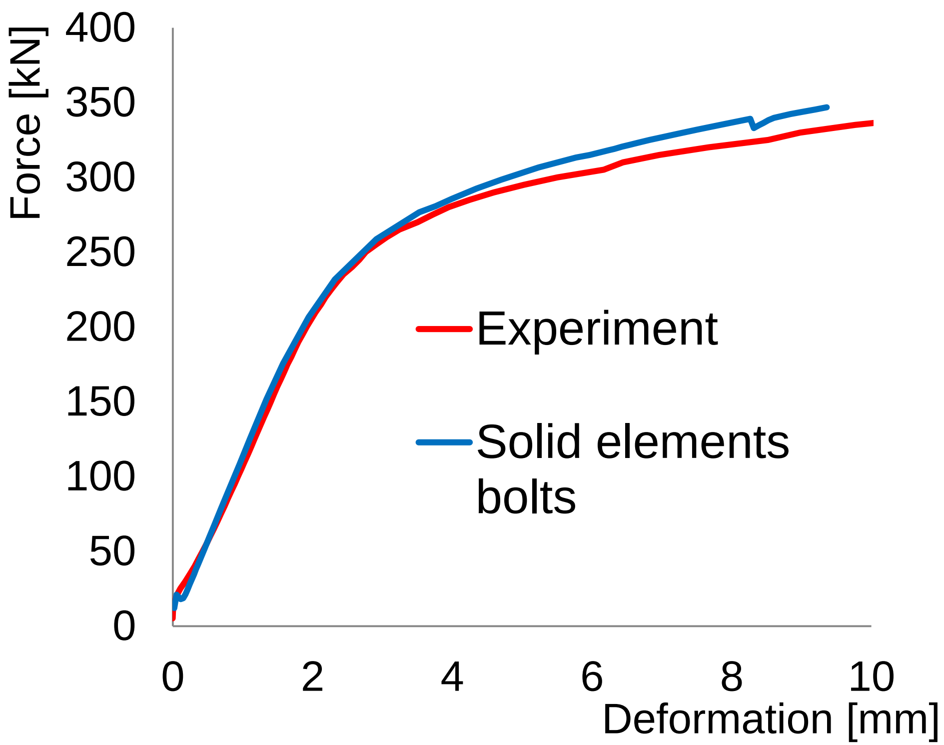
Testing machine

Validation of research model of T-stub in tension

- The Figure shows the validation of the research oriented model of T-stub from HEB300 loaded in tension.



Research oriented model of T-stub



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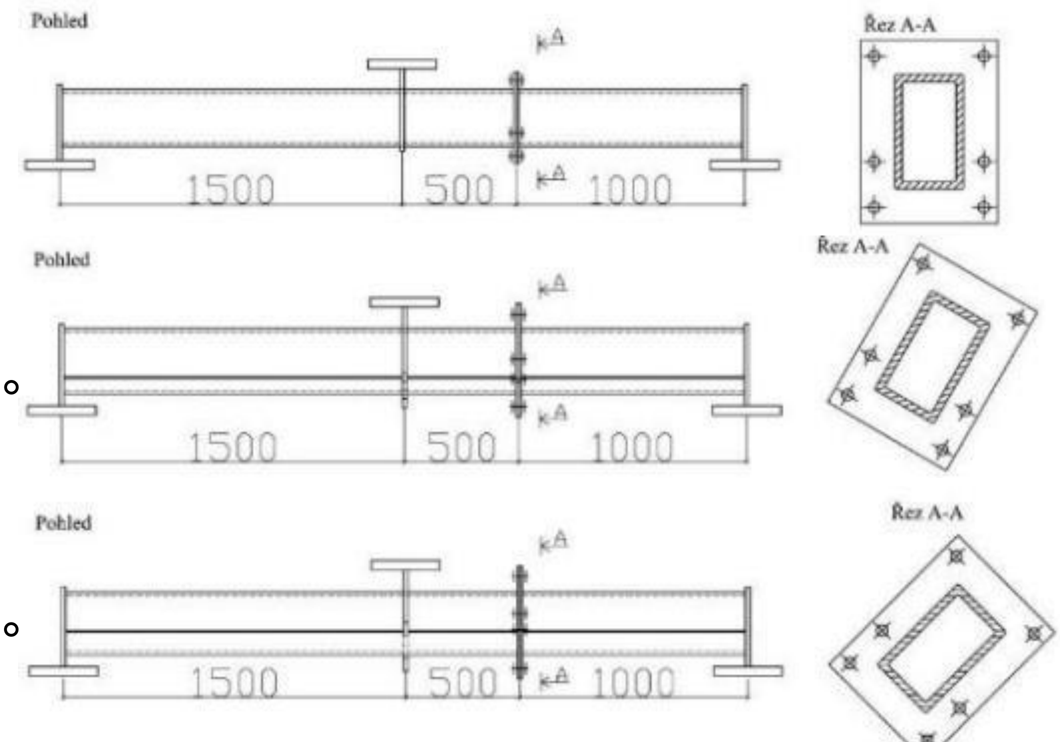
Experiments with generally positioned end plates

- The experiments were prepared with three bolted beam to beam end plate connections.

0°

30°

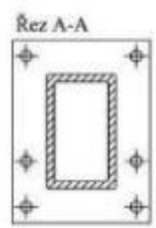
45°

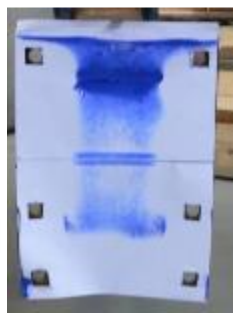


Parameters of speciments for the generally positioned end plate

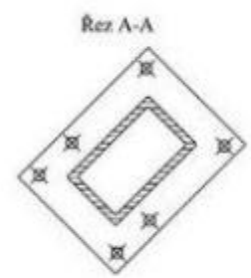
- Plate **P20** – 400 x 300 mm
- Steel **S355** ($f_{y,exp}$ = 410 MPa; $f_{u,\,exp}$ = 582 MPa)
- Bolts **M20** - 8.8
- Pitches vertical (35 – 230 – 100 - 35 mm)
  horizontal (30 – 240 – 30 mm)

0°

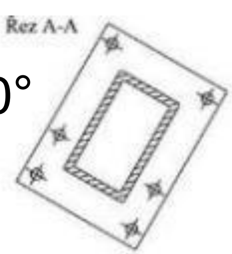




45°



30°



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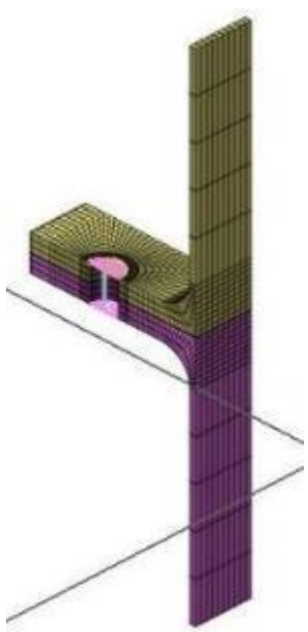
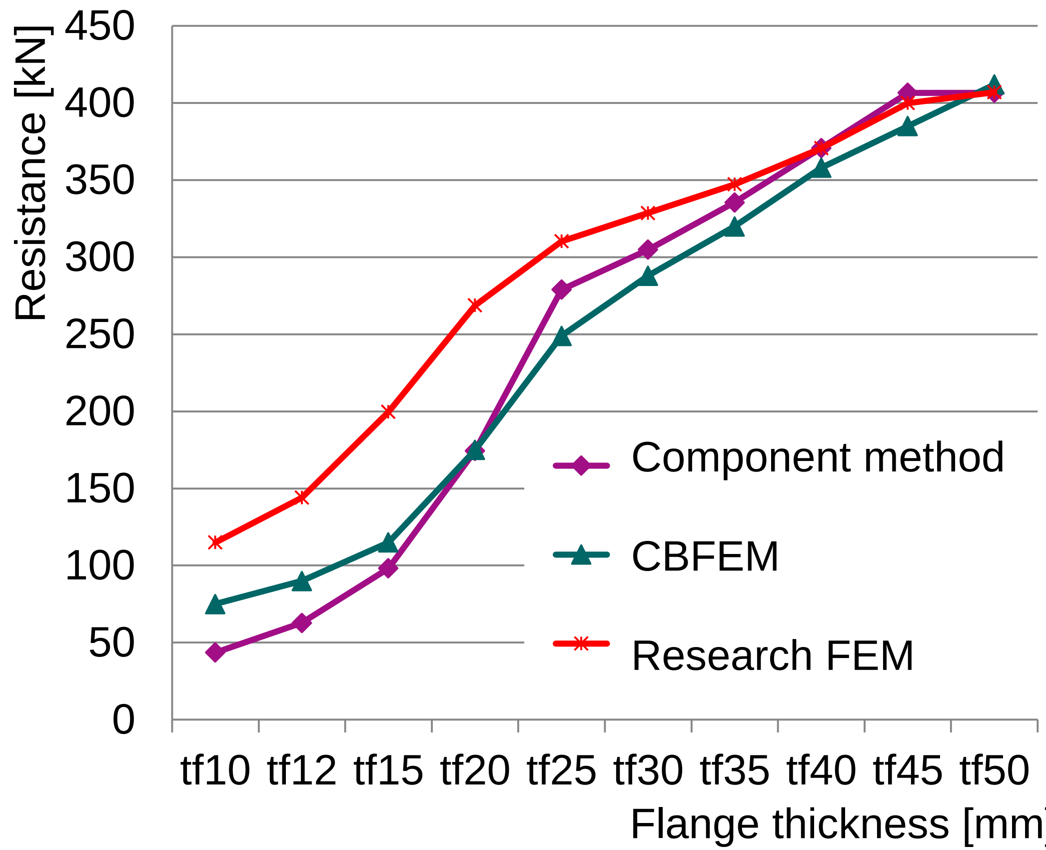
Verification of T-stub in tension

- The Figure shows the verification of the design oriented model of T-stub from HEB300 loaded in tension to research oriented FE model. Comparison to component method is included.

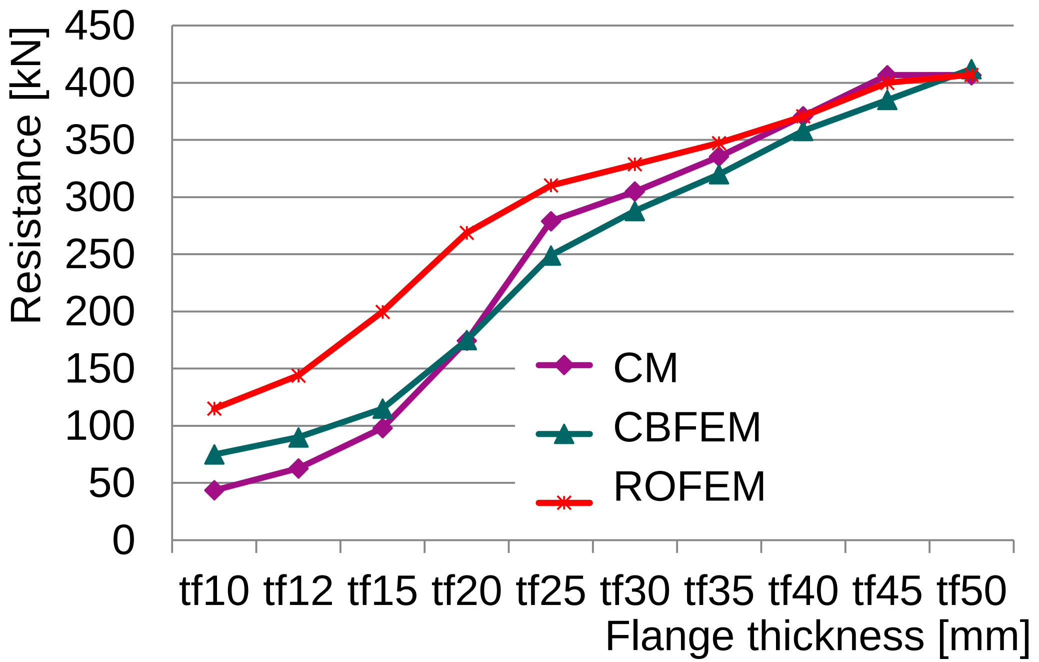


Design oriented model of T-stub



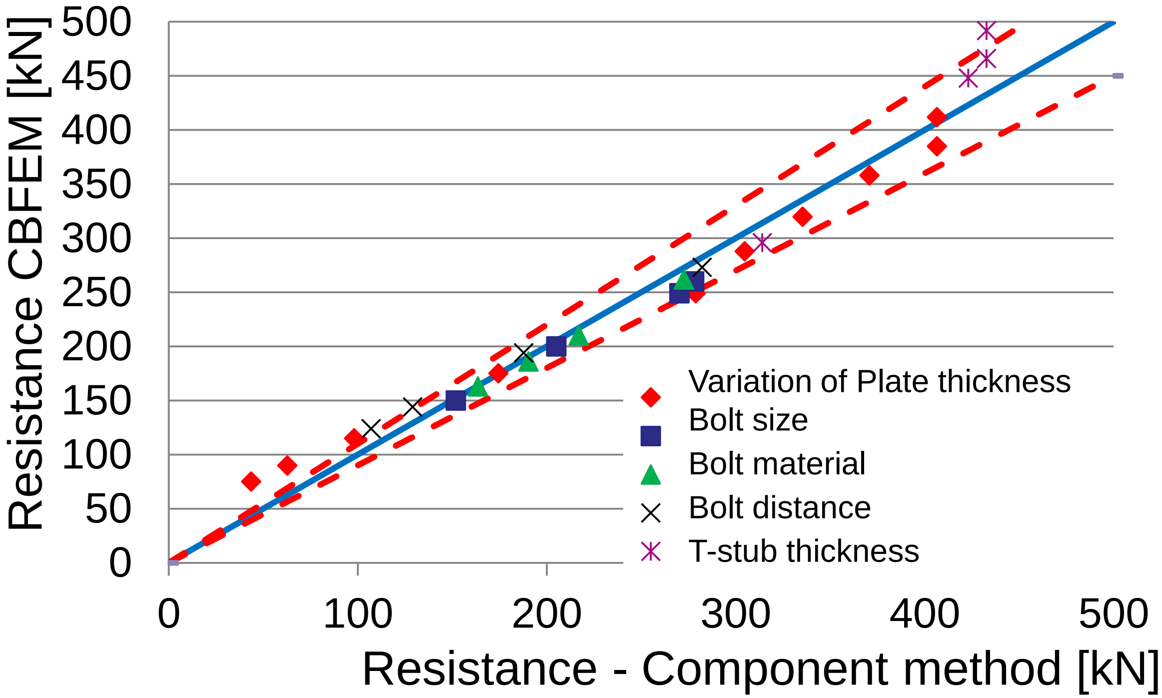
Verification of T-stub in tension

- The sensitivity study of thickness of the flange shows higher resistance according to CBFEM compared to CM for samples with flange thicknesses up to 20 mm.
- ROFEM gives even higher resistance for these samples.
- Higher resistance of both numerical models is due to neglection of membrane effect in CM.



Verification of T-stub in tension

- To show the prediction of the CBFEM model, results of the studies are summarized in graph comparing resistances by CBFEM and component method. The results show that the difference of the two calculation methods is mostly up to 10%.
- In cases with CBFEM/CM > 1,1 accuracy of CBFEM is verified by the results of Research oriented FEM, which gives highest resistance in all selected cases.

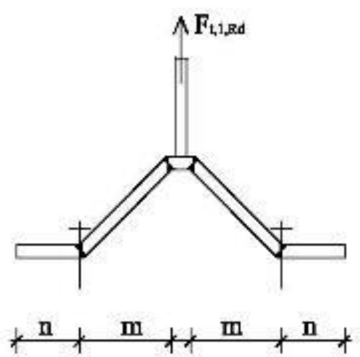


Verification of T-stub in tension

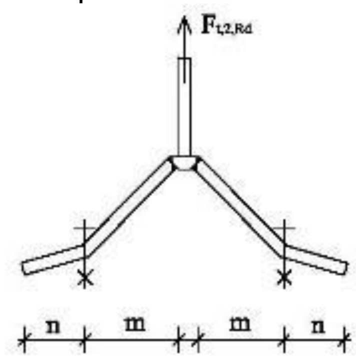
- Three failure modes of T-stub are considered.

Component Method

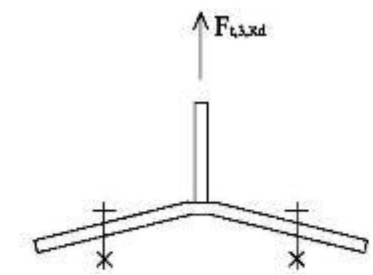
Full yielding of flange



Yielding of flange and rupture of bolts



Rupture of bolts



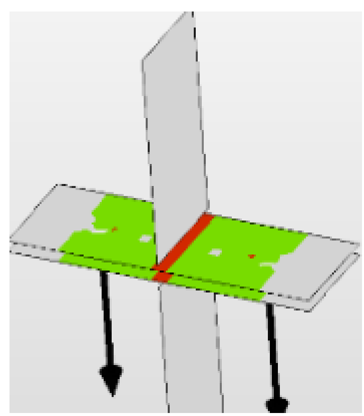
$$F_{t,1,Rd} = \frac{(8n - 2e_w) M_{pl,1,Rd}}{2mn - e_w(m+n)}$$

$$F_{t,2,Rd} = \frac{2M_{pl,2,Rd} + 2nF_{t,Rd}}{m+n}$$

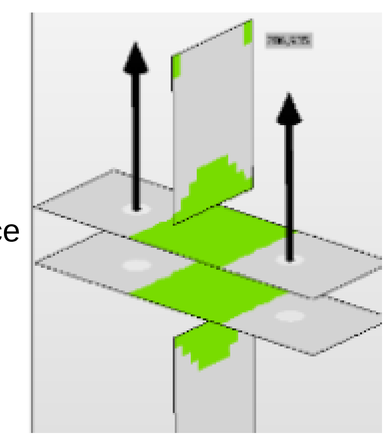
$$F_{t,3,Rd} = 2F_{t,Rd}$$

Component Based FEM

Yielding of flange

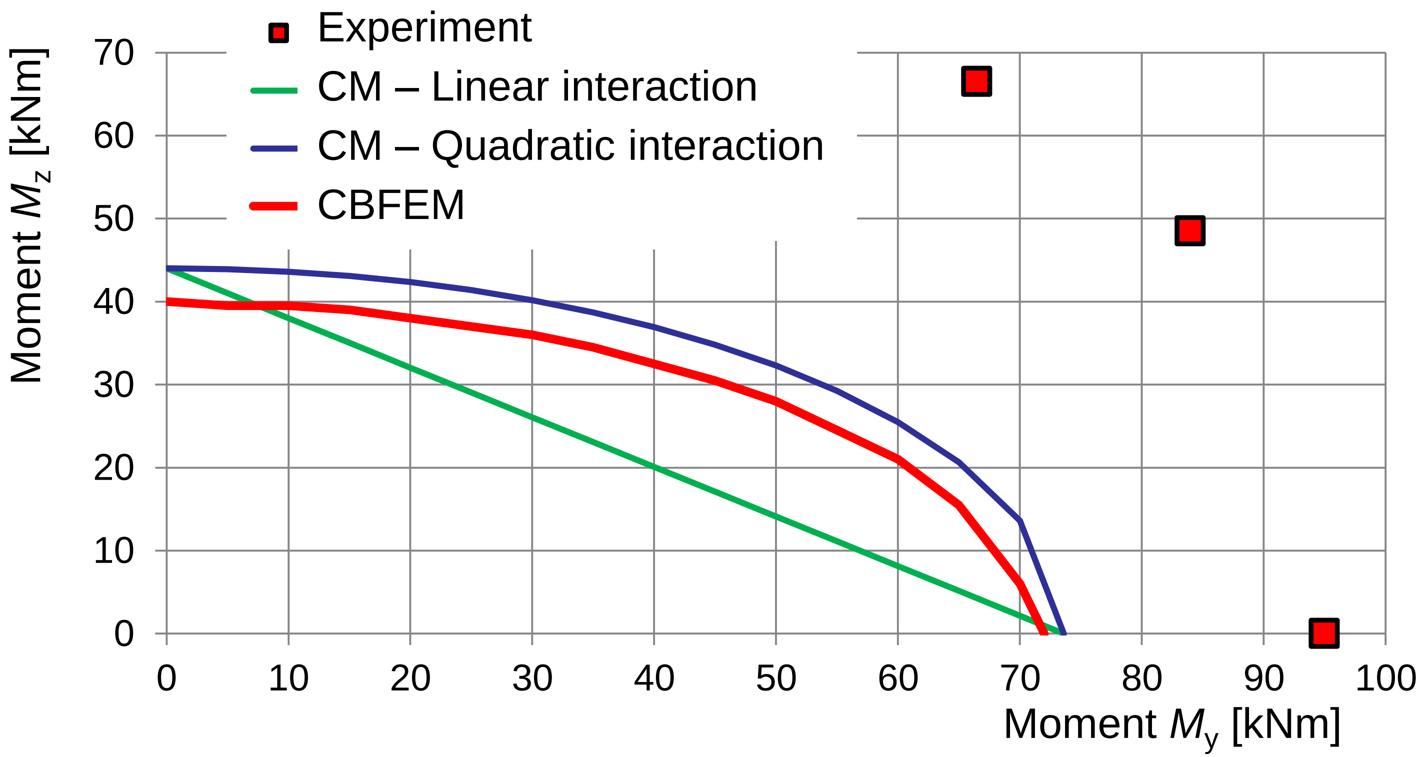


Bolt resistance



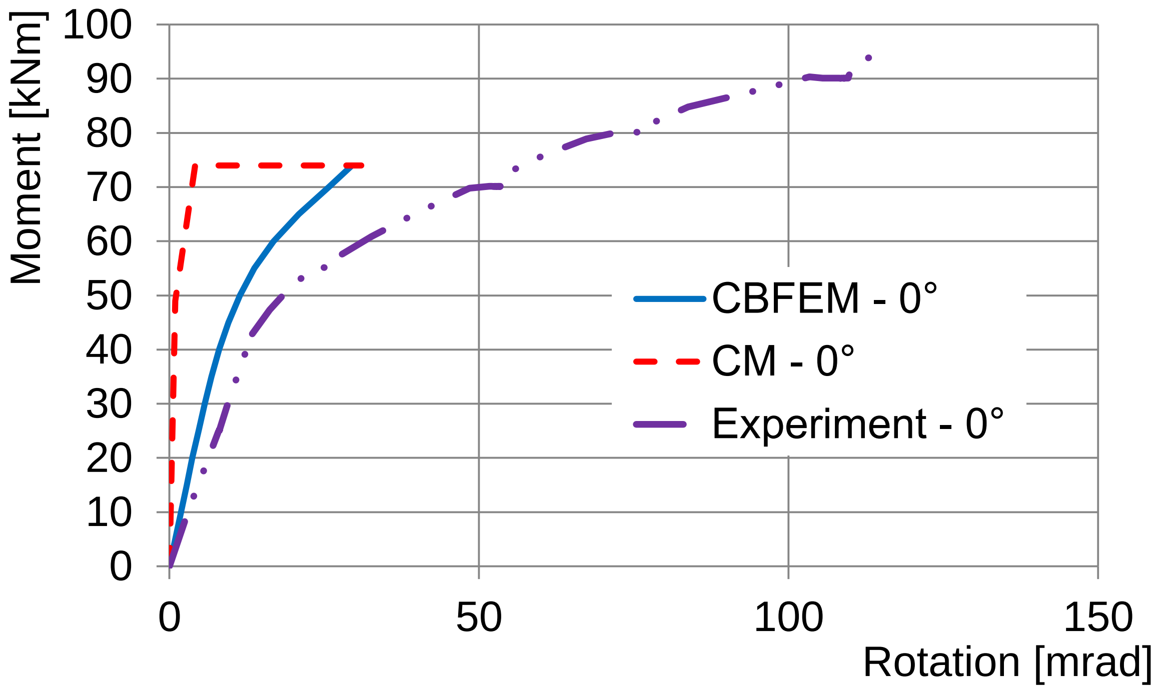
Verification of generally loaded end plate

- Resistance calculated by CBFEM is compared with the results of CM and experimental results. The sensitivity study is focused on ratio of bending moments in strong and week axis, see Figure below.
- CM with linear interaction gives conservative values of resistance.
- CM with quadratic interaction gives the highest resistances, which are to experimental results still rather conservative.
- CBFEM gives similar results as CM with quadratic interaction.



Verification of end plate

- Comparison of the global behaviour described by moment-rotation diagram is prepared. Attention is focused to initial stiffness, resistance and deformation capacity.
- Sample 0° with strong axis bending moment is chosen to present as reference, see Figure below.
- CM gives higher initial stiffness compared to CBFEM and experimental data.
- Resistance predicted by CM and CBFEM are similar.
- Experimentally reached resistance is higher.



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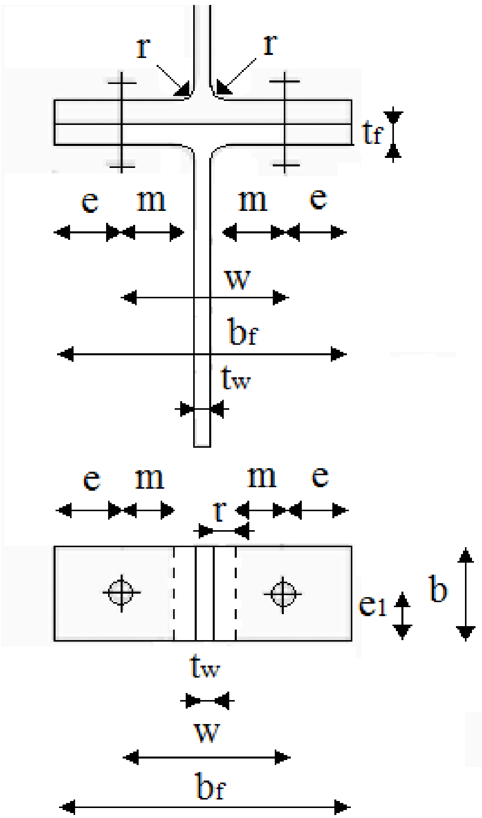
Benchmark case T-stub

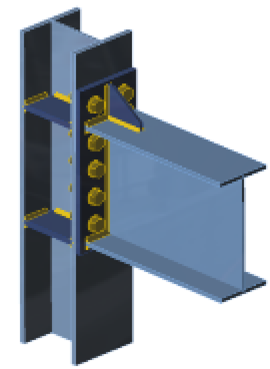
- **Inputs**
- T-stub
  - Steel S235
  - Flange thickness t_f = 20 mm
  - Web thickness t_w = 20 mm
  - Flange width b_f = 300 mm
  - Length b = 100 mm
  - Double fillet weld a_w = 10 mm
- Bolts
  - 2 x M24 8.8
  - Distance of the bolts w = 165 mm
- **Outputs**
  - Design resistance in tension $F_{T,Rd}$ = 175 kN
  - Collapse mode - full yielding of the flange with maximal strain 5 %
  - Utilization of the bolts 88,4 %
  - Utilization of the welds 49,1 %

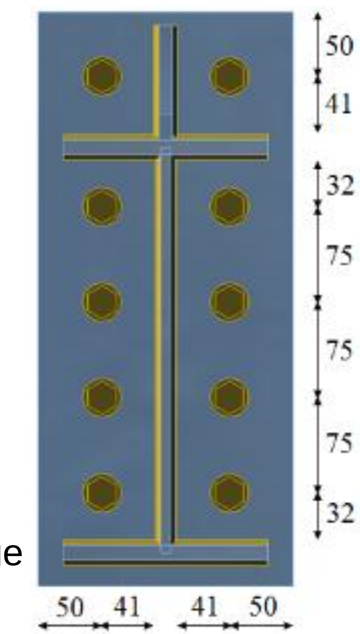


Benchmark case
end plate connection

Introduction
Design models
Global analyse
Classification
Component meth.
Interaction
Assessment I
CBFEM
General
Validation
Verification
❯ Benchmark case
Assessment II
Summary

- **Inputs**
  - Steel S235
  - Beam IPE 330
  - Column HEB 300
  - End plate height h_p = 450 (50-103-75-75-75-73) mm
  - End plate width b_p = 200 (50-100-50) mm
  - End plate P15
  - Column stiffeners 15 mm thick and 300 mm wide
  - End plate stiffener 10 mm thick and 90 mm wide
  - Flange weld throat thickness a_f = 8 mm
  - Web weld throat thickness a_w = 5 mm
  - Bolts M24 8.8
- **Outputs**
  - Design resistance in bending M_{Rd} = 209 kNm
  - Corresponding vertical shear force V_{Ed}= 209 kN
  - Collapse mode - yielding of the beam stiffener on upper flange
  - Utilization of the bolts 89,5 %
  - Utilization of the welds 87,2 %





Assessment II

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- How is limited plastic strain for design of resistances of plates?
- How is simplified the convergence of finite elements procedure of steel members and plates?
- How is modelled the bolt model in CBFEM?
- How is modelled interaction bolts loaded at the same time in shear and tension?
- As how is transferred the shear force as the slip resistance bolt reach its resistance?
- Why is filled weld modelled by equivalent solid elastoplastic element, which is added between plates?
- How differs validation from verification?
- What are two major purposes of benchmark cases in application of FEA analyses?

Summary

Lecture 1

Beam to column moment connection

Summary

- The design of beam to column moment connections is focussed to preferable yielding of steel plates and brittle failure of fasteners, bolts, welds.
- The design of beam to column moment connection by Component Method (CM) is very accurate in components behaviour modelling.
- The lever arm is in CM estimated based on the best engineering practice. Its prediction is good in well know and tested connections and joints. Its educated guess affects the resistance.
- The CM is prepared for software tools and design tables not for had calculation.

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Summary

- The design of connections by finite element method is not replication of the physical experiment. The designer is interested into the limited yielding of steel plates and failure of fasteners.
- Component based finite element method (CBFEM) is taking advantage of accurate modelling of component behaviour based on experiment and accuracy of discrete analyse of steel plate by FEM
- The Validation and Verification procedure is integral part of any finite element analyses. The procedure is checking the software and the use by designer.
- CBFEM offers the designer a discrete view on the behaviour, see next slides.

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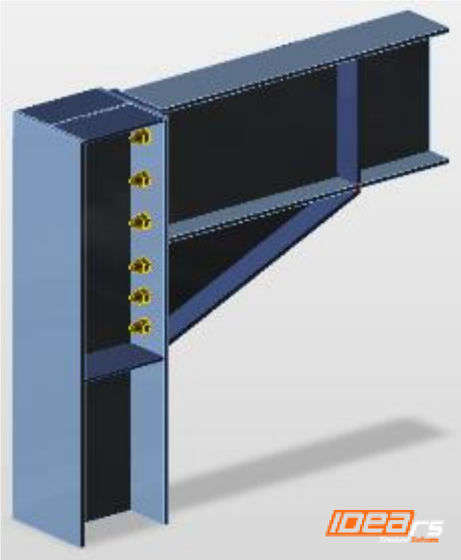
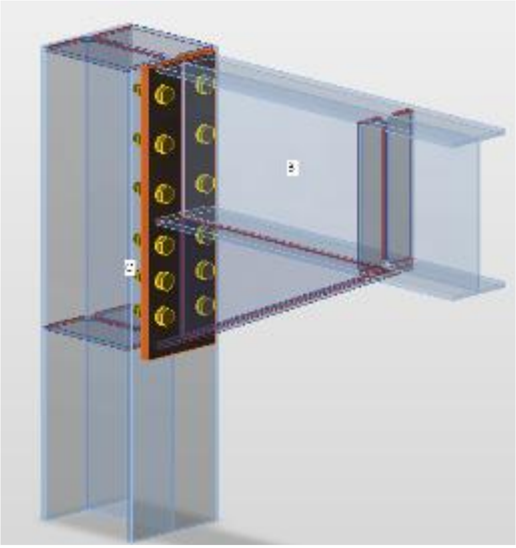
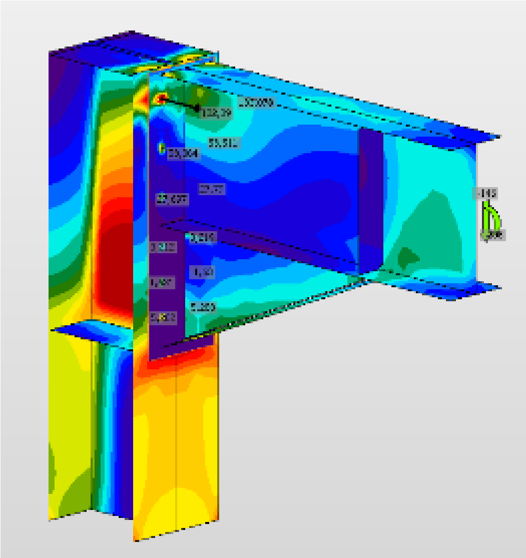
Prediction of global and local behaviour

Beam to column connection

- Full depth end plate 25 mm
- Rafter IPE 400
- Column HEA 320
- 12 bolts M24 8.8
- Haunch 700x300 mm
- Flange 15x150 mm
- Stiffeners P20
- Steel S355







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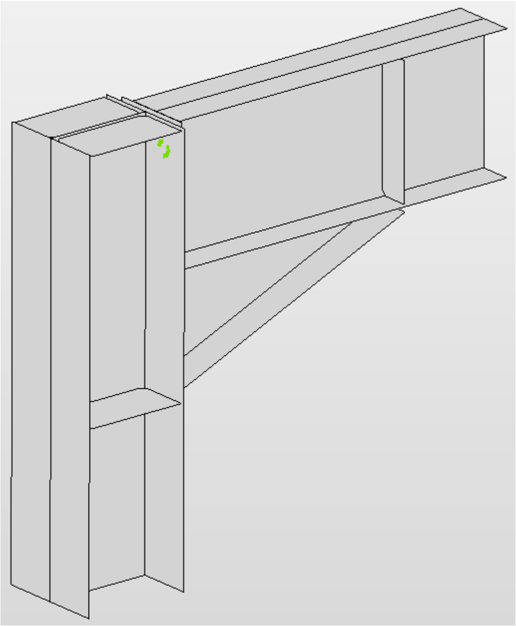
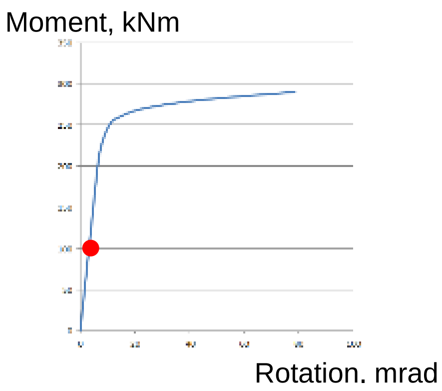
Global and local behaviour



M = 100 kNm

Fi = 3,2 mrad

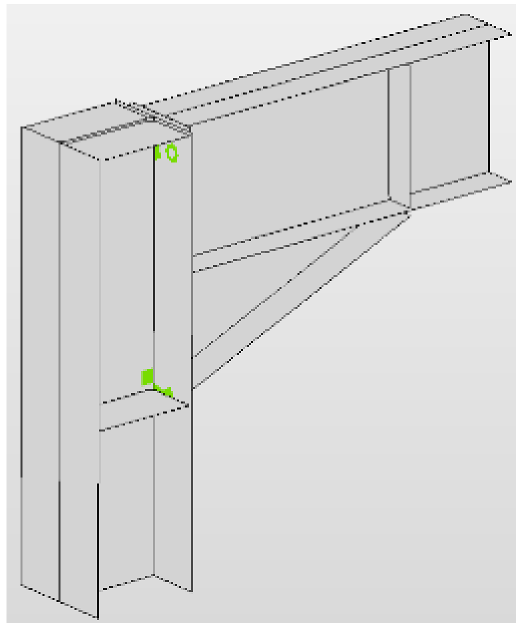
Si = 31,6 MNm/rad



Column flange plastification round bolts

Well designed steel connection starts to classify early to allow plastic distribution of forces between connectors.

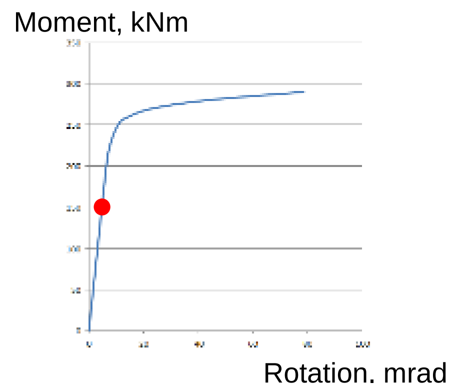
Global and local behaviour



M = 150 kNm

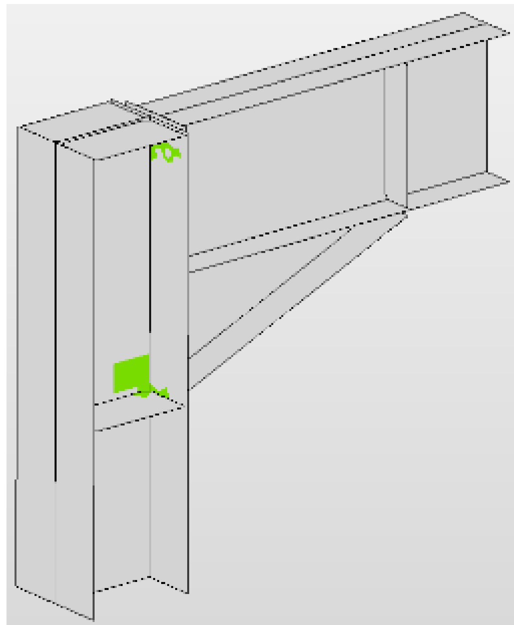
Fi = 4,8 mrad

Si = 31,6 MNm/rad



Column web plastification

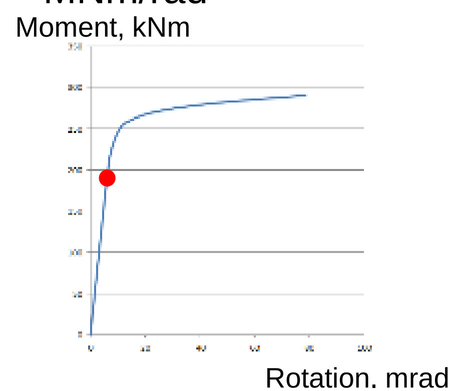
Global and local behaviour



M = 180 kNm

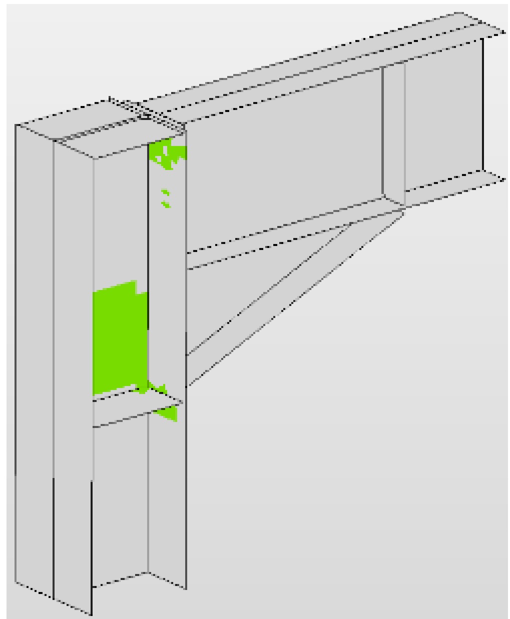
Fi = 5,7 mrad

Si = 31,5 MNm/rad



Progress of column web plastification

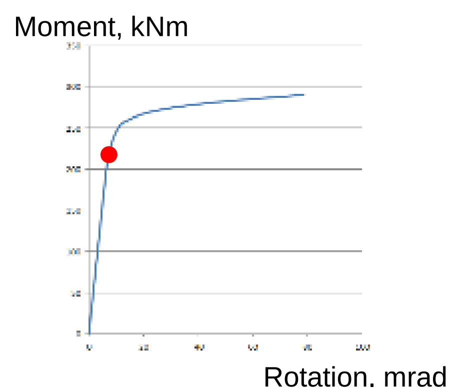
Global and local behaviour



M = 220 kNm

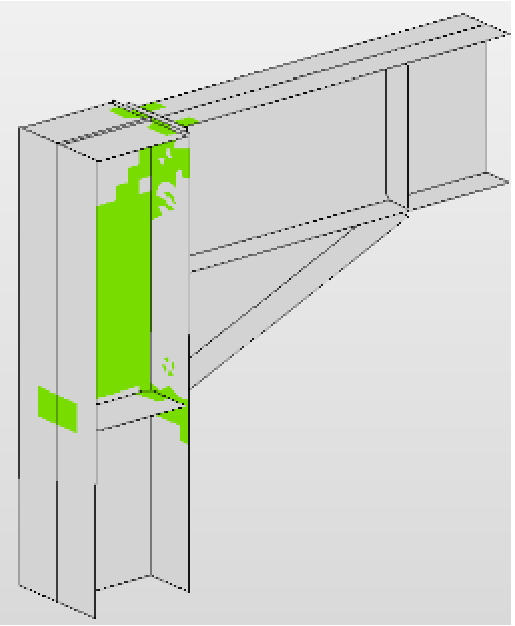
Fi = 7,3 mrad

Si = 30,0 MNm/rad



Progress of column web plastification

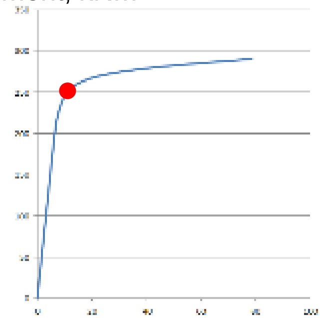
Global and local behaviour



M = 250 kNm

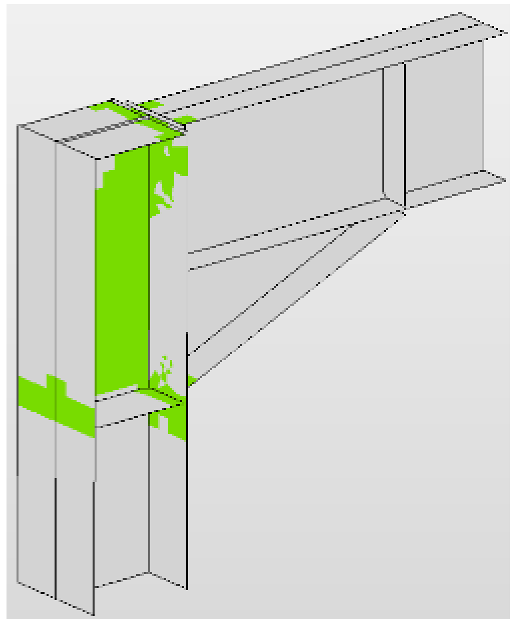
Fi = 10,7 mrad

Si = 23,4 MNm/rad



Column web full plastification

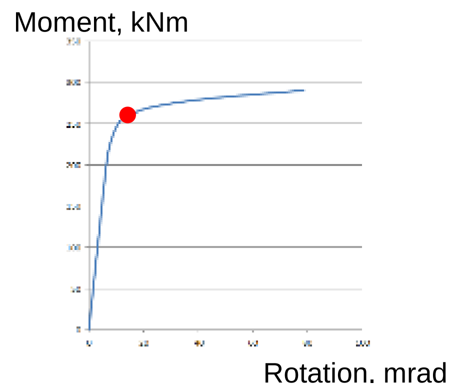
Global and local behaviour



M = 260 kNm

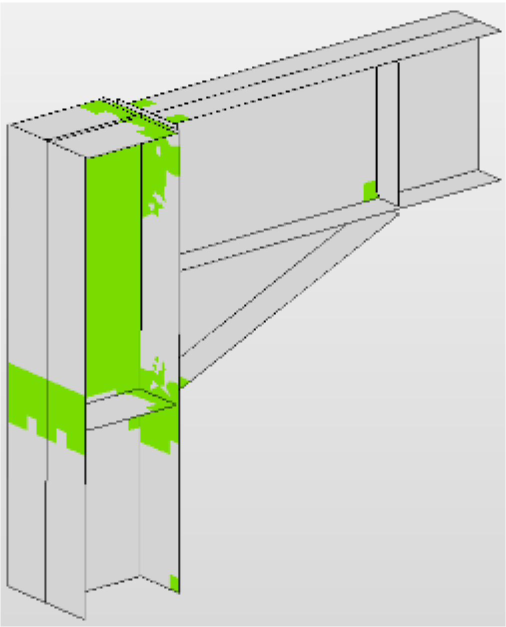
Fi = 14,7 mrad

Si = 17,4 MNm/rad



Column flange on opposite side plastification

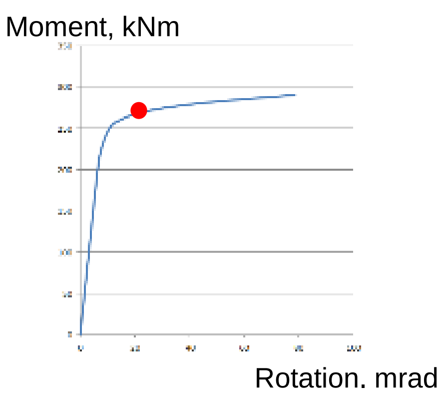
Global and local behaviour



M = 270 kNm

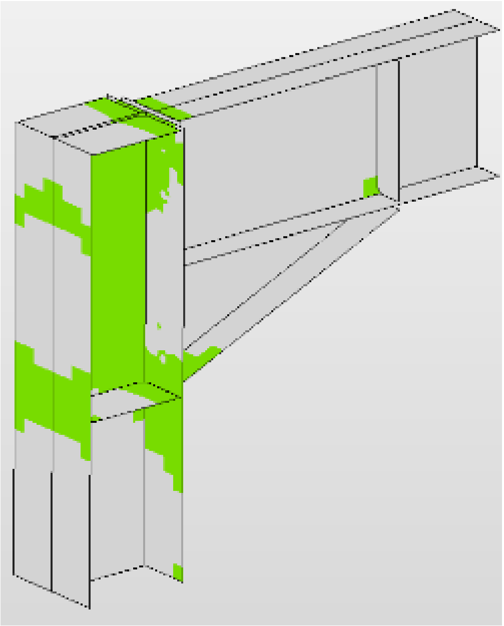
Fi = 23,4 mrad

Si = 11,5 MNm/rad



Beam above haunch starts yield

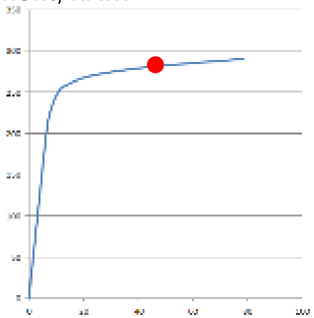
Global and local behaviour



M = 280 kNm

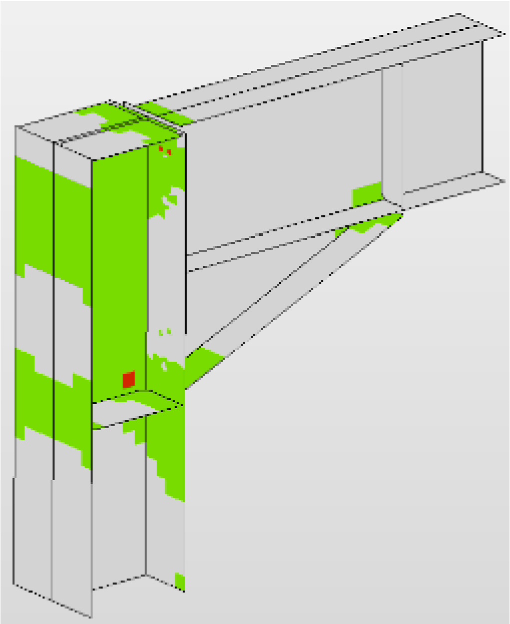
Fi = 43,6 mrad

Si = 6,4 MNm/rad



Further plastification

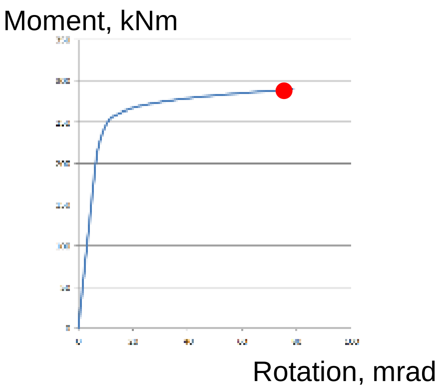
Global and local behaviour



M = 290 kNm

Fi = 78,6 mrad

Si = 3,7 MNm/rad



Resistance reached

- By 5% strain in column web loaded in shear and compression.
- **Well designed steel connection** starts to plasticize early
  to allow plastic distribution of forces between connectors/plates.

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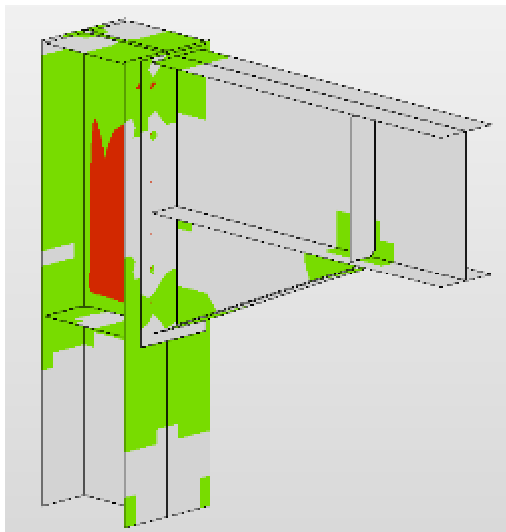
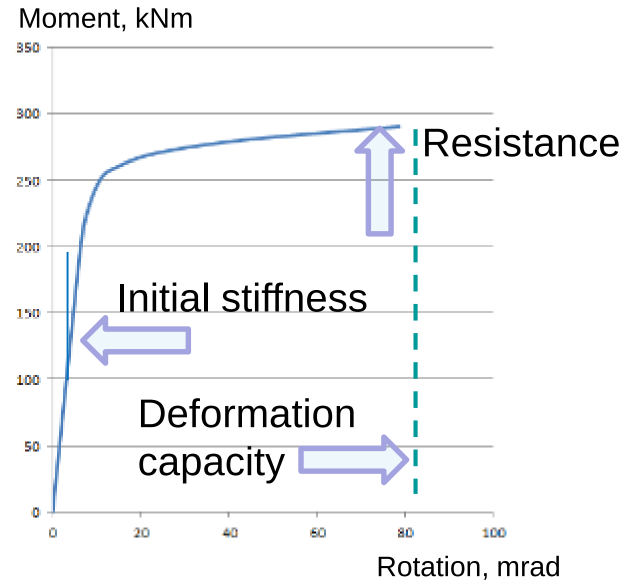
Global and local behaviour





The major joint in bending design characteristics

where $S_{j,ini}$ is the initial stiffness,

$M_{j,Rd}$ is the design bending resistance,

φ_{Cd} is the deformation capacity

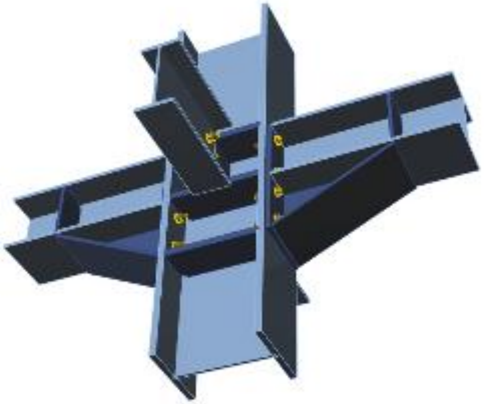
are well described.

What is the major reason

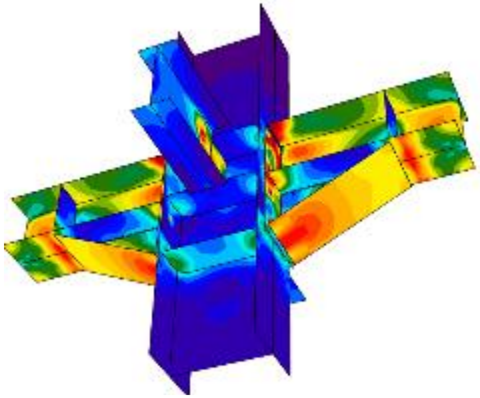
of using CBFEM for Beam to column moment connections?

- **Generally loaded complex joints**
  is difficult to design in space accurately by Component or other methods.

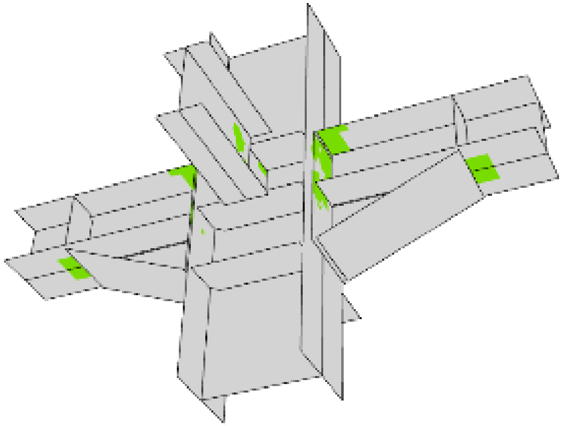
- The example of design procedure by CBFEM is shown below.



3D model



Finite element analyses



Design check

Thank your for attention

URL: steel.fsv.cvut.cz

František Wald, Lukáš Gödrich, Marta Kuříková
Luboš Šabatka, Jaromír Kabeláč, Drahoš Kojala

Notes to users of the lecture

- Subject Design of the open sections joints.
- Lecture duration 60 mins.
- Keywords Civil Engineering, Structural design, Steel structure, Beam to column connection, Beam to beam connection, Beam spices, Open section, Joint, Component Method, Component based Finite Element Method, Eurocode.
- Aspects to be discussed Experiments, Reasons and methods of classification, Principles of CM, Major components in CM, Interaction of forces, Components in CBFEM, Principles of CBFEM, Validation and Verification.
- Further reading relevant documents in references and relevant European design standards, Eurocodes including National Annexes.
- Preparation for tutorial exercise see examples in References.

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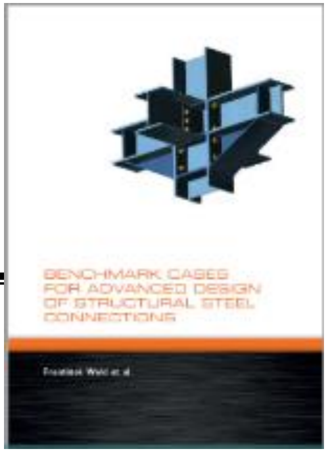

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