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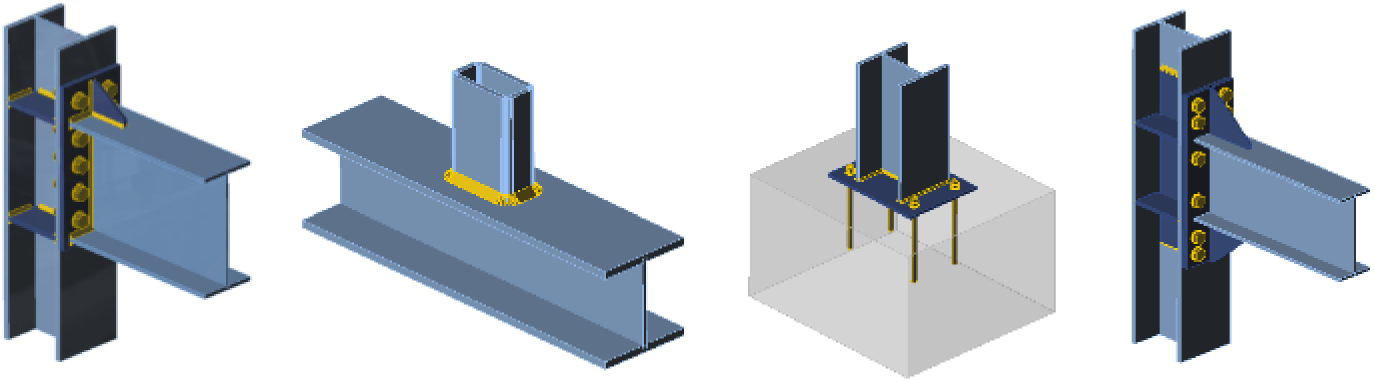
Connection design by Component Based Finite Element Method

Lecture 2
Joint of hollow to open section

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 modelling of hollow section joints
- Provide an online training to students and engineers
- Introduce principles of Failure Mode model
- Introduce principles of Component Based Finite Element Method (CBFEM)
- Show the process of Validation & Verification
- Offer list of references relevant to the topic

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Lecture 2

Joint
of hollow to open section

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Lubomír Šabatka, Jaromír Kabeláč, Drahoš Kojala

Tutorial

- This lecture describes principles
  of **FEM modelling** of hollow section joints
  by applying the Component Based FEM (CBFEM).
- The failure mode models are presented on one of the most simple case on hollow to open section joints.
- Survey of both simple and FEM analyses
  and modelling is shown.
- 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.

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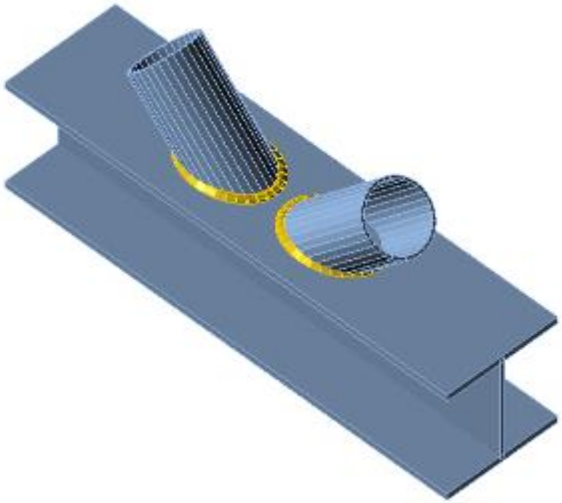
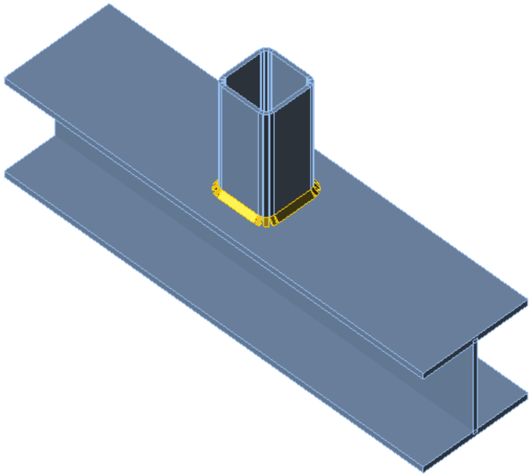
Motivation

- The aim of this lecture is
  to explain the design of hollow sections joints
  on joints
  of hollow sections to open sections,
  as a simple case of very large subject.





Outline of the lecture

- Introduction - hollow section joints
- **Failure mode method**
  - General
  - Influencing joint parameters
  - Component method
  - Hollow to open joints
  - Assessment I
- **Component based FE method**
  - Principles
  - Validation
  - Verification
  - Benchmark case
  - Assessment II
- Summary

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Hollow section joints

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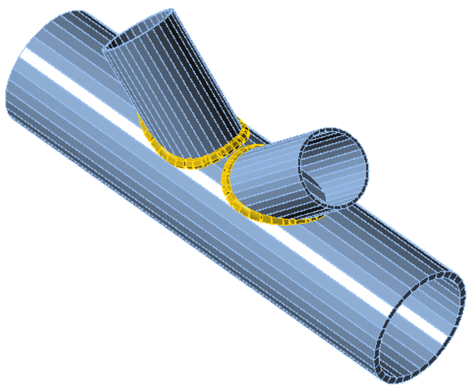
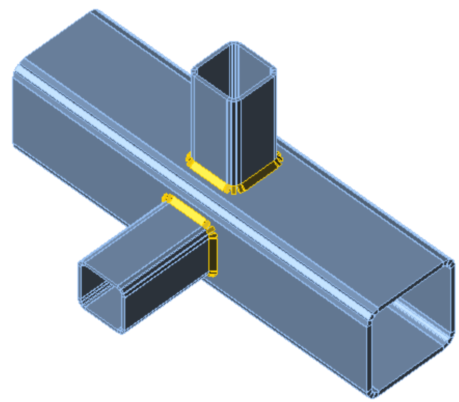
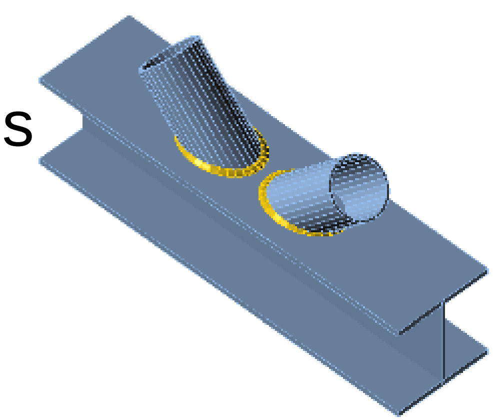
Joint of hollow to open section

Geometry

- The welded joints of circular, square or rectangular hollow sections can be either:
  - Uni-planar
  - Multi-planar

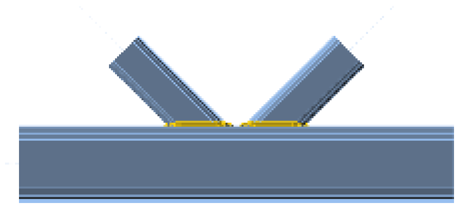



- The combination of hollow sections with open sections are used in the uni-planar joints.

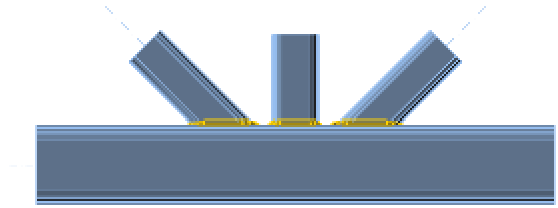


Basic geometrical types

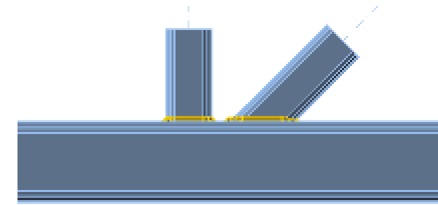
- The typical uni-planar joints



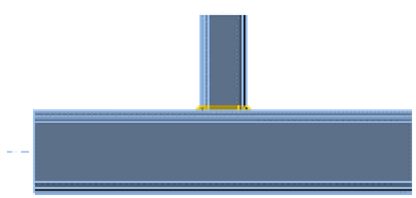
K joint



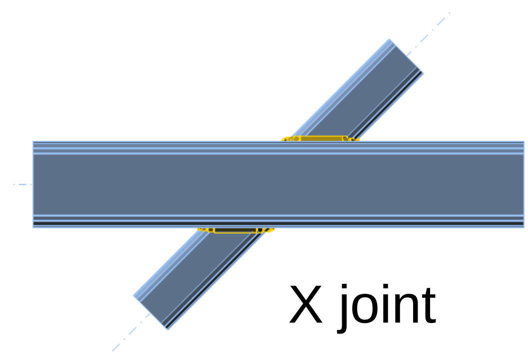
KT joint



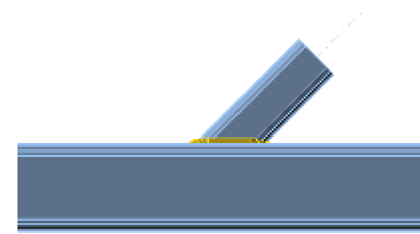
N joint



T joint



X joint



Y joint

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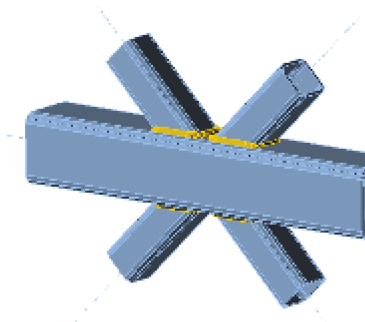
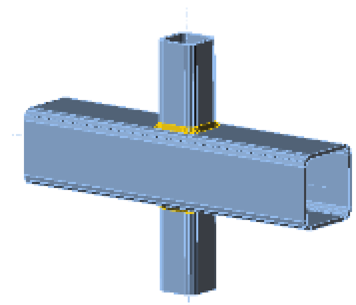
Basic geometrical types

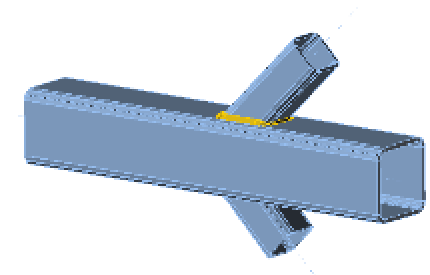
- The typical multi-planar joints



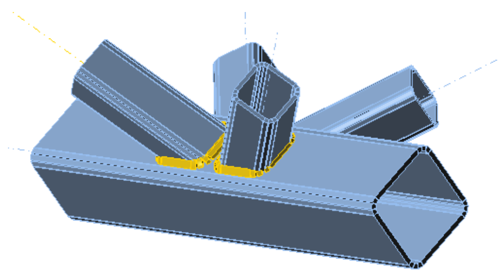
DK joint



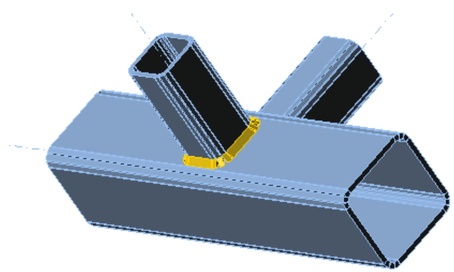
X joint



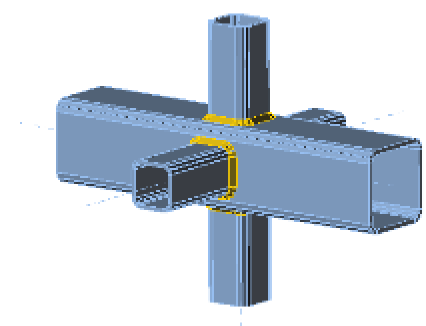
DY joint



KK joint



TT joint



XX joint

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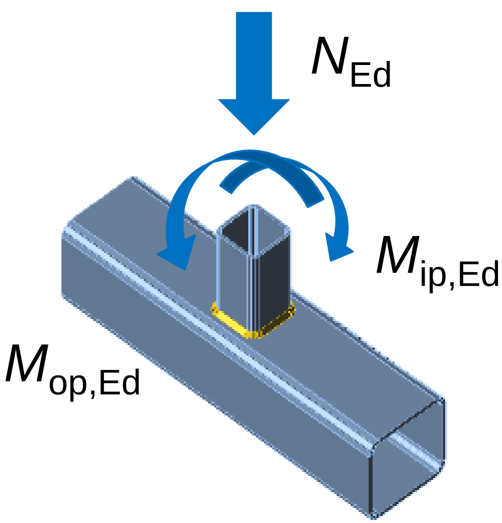
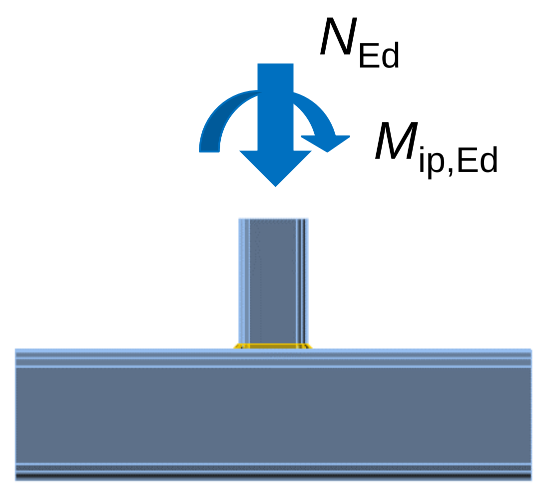
Loading

- The design resistance of the joint is expressed as maximum axial or moment resistances for the brace.
- The moment resistance can be reached for in-plane or out-of-plane loading.





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Design of welds

- The welds are preferably designed for full resistance of joint not be the weakest part. I.e. the design resistance of the weld, per unit length of perimeter of a brace member, should not normally be less than the design resistance of the cross-section of that member per unit length of perimeter.
- **The full seam butt weld** is recommended for $t_i > 8$ mm with $a = t_i$
- **The fillet welds** are recommended only for members thickness $t_i \leqslant 8$ mm with the weld effective thickness a for element thickness t_i and for steel

S 235 as	$a = 0{,}92\ t_i$
S 275 as	$a = 0{,}96\ t_i$
S 355 as	$a = 1{,}10\ t_i$
S 420 as	$a = 1{,}42\ t_i$
S 460 as	$a = 1{,}48\ t_i$

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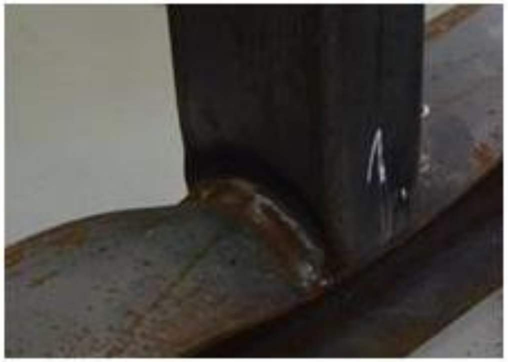
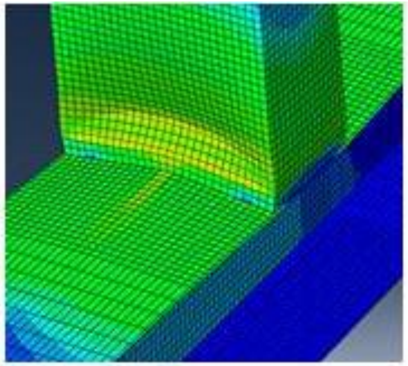
Design methods

Design resistance of joints may be determined by:

- **Failure mode method** based on
  - Curve fitting procedures with derived joint parameters based on analytical models
- **Component method**
  - Using lever arms and component resistances determined according to a failure mode procedure
- **Finite element method**





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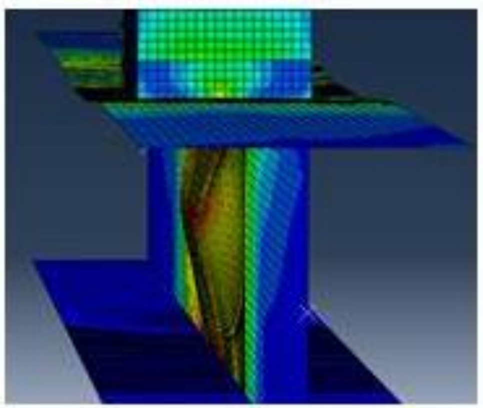
Finite element method

- **Research oriented model** by numerical experiments with geometric and material non-linear analysis with imperfections and evaluation of safety as mechanical experiments according to EN1990.



- **Design oriented model** with geometric and material non-linear analysis using design material model.
    - The **Component based FEM (CBFEM)** is design procedure combining analytical models for components and FE analysis of plates.

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Failure mode model

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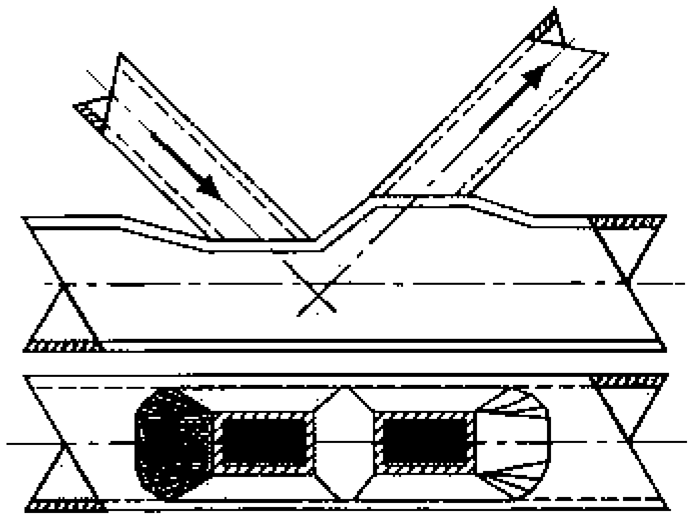
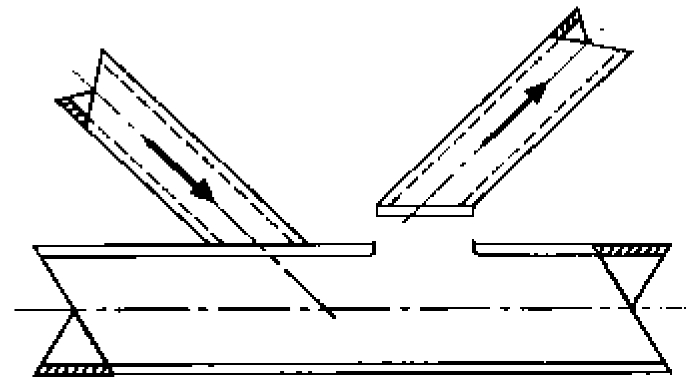
Joint of hollow to open section

Failure modes on chord

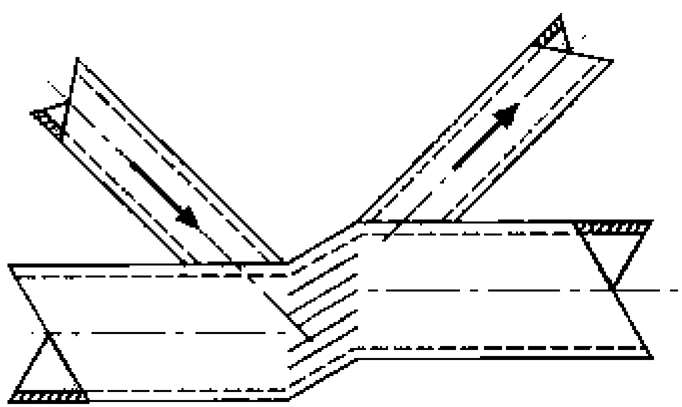
demonstrated on rectangular hollow sections (RHS)



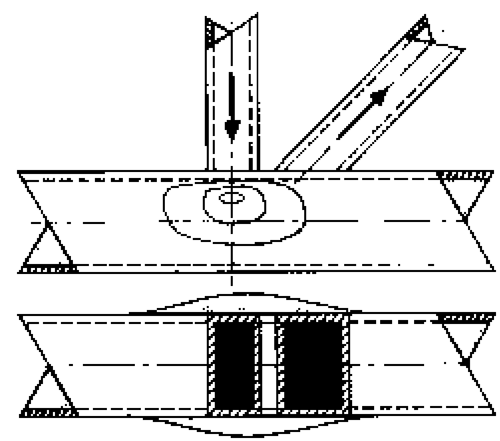
Chord face failure



Punching shear failure
of the chord face



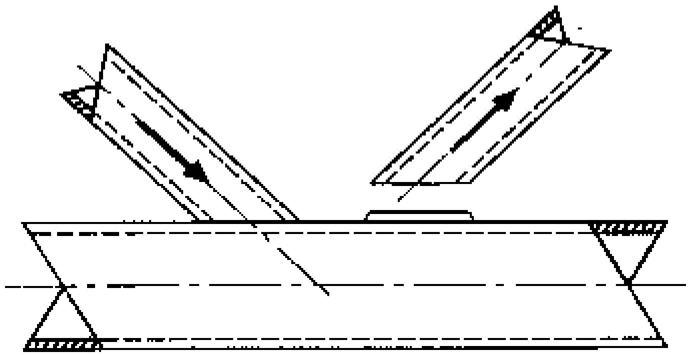
Overall shear
failure of the chord



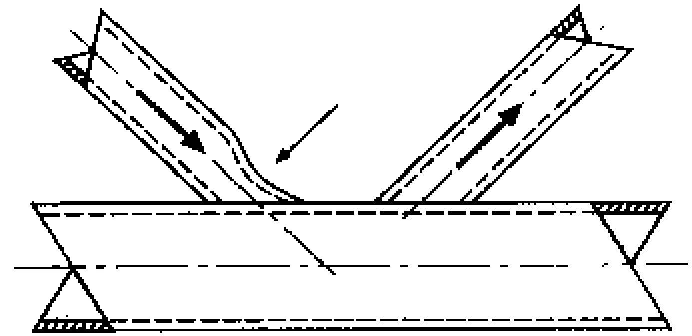
Chord side wall failure

Failure modes on brace

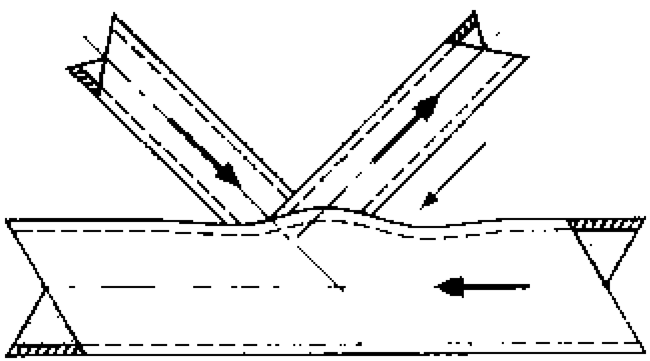
demonstrated on rectangular hollow sections (RHS)



Brace failure



Local buckling
of the brace member



Local buckling
of the chord face

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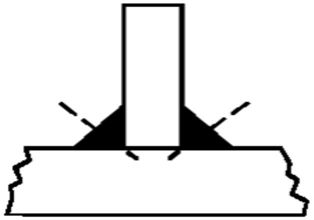
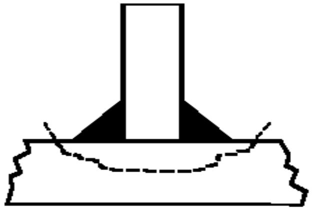
Excluded modes of failure

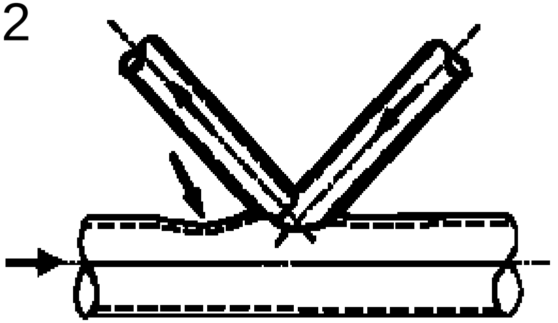
- Weld failure
  - Excluded by use efficient throat thickness of the welds



- Lamellar tearing
  - Excluded by material properties



- Local buckling of the chord or brace sections
  - Excluded by using sections with can be classified to a maximum cross section class 2



Design principle

- **Welds** are designed for full sectional resistance.
- **Geometrical types** are selected.
- **Range of validity** is prepared based on available experiments for each geometrical type.
- Limited number of **failure modes** is possible by each geometrical type.
- For each geometrical type is prepared for each failure mode a **curve fitting prediction** of resistance.
- The **influencing joint parameters** are derived based on five **analytical models.**

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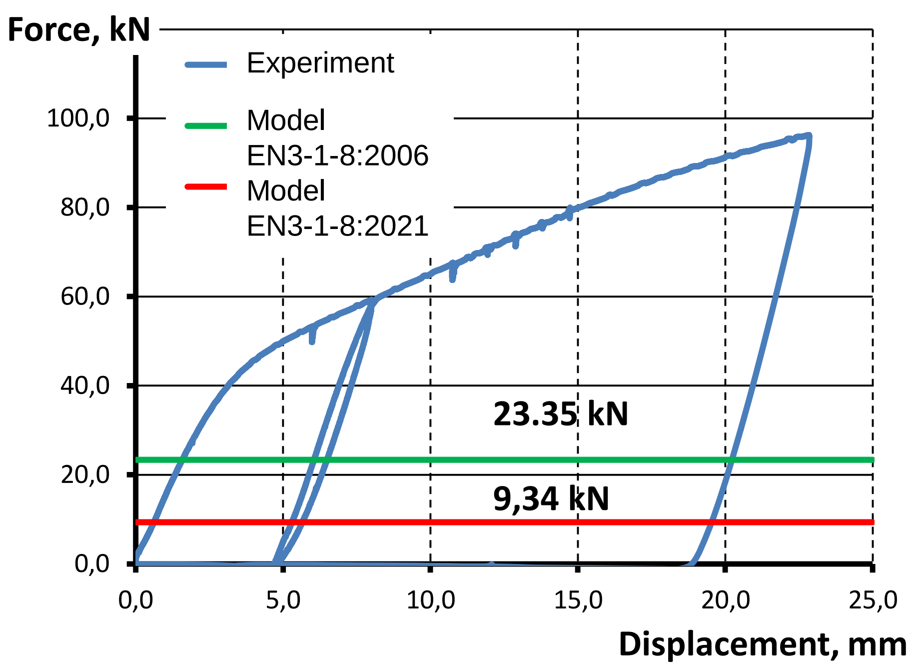
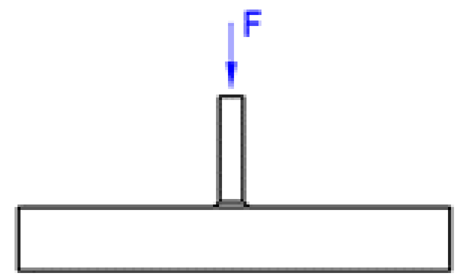
Experiments and design resistance by curve fitting procedures

The design resistance is derived from experiments from

- Ultimate load (in EN1993-1-8:2005)
- Deformation limit (in prEN1993-1-8:2017)
  - chord width as $b_0/300$





Example behaviour and curve fitting predictions of joint with RHS chord 150 x 100 x 4 mm and brace 50 x 30 x 4 mm

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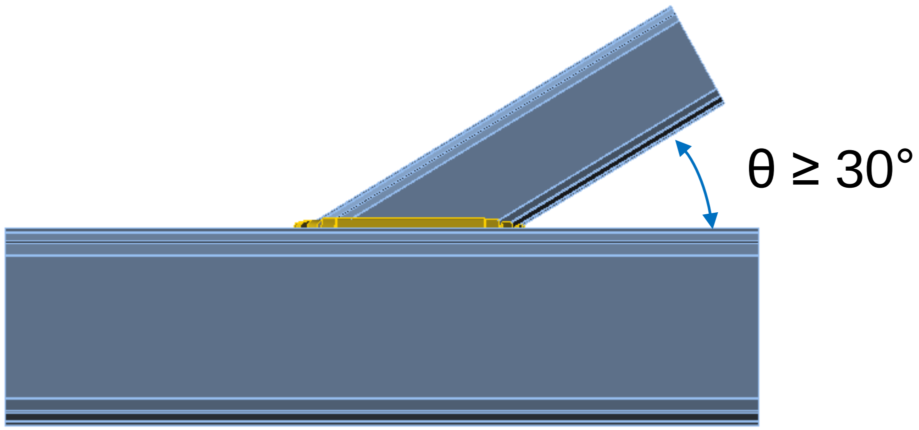
General limits of application

- The members of lattice structures should satisfy the requirements:
- Class 1 (or Class 2) cross section only
- The angle between the brace and the chord should be larger than 30°



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Analytical Models

for determination of influencing joint parameters

- The curve fitting procedure is used for evaluation of joint´s resistance on each possible failure mode.
- For the determination of **the influencing joint parameters** of welded joints between rectangular hollow sections are used analytical models:
  - Yield line
  - Punching shear
  - Brace effective width
  - Chord side wall bearing or buckling
  - Chord shear

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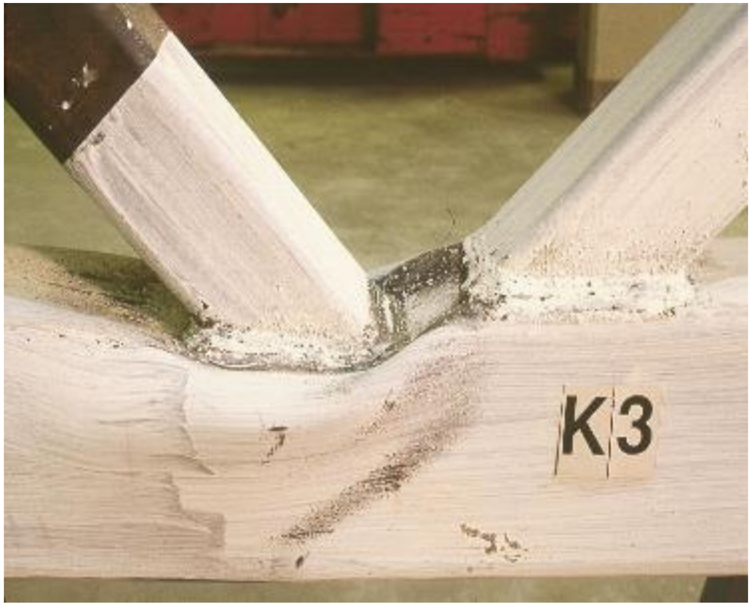
Yield line model
for the influencing joint parameters

- The typical case of searching for influencing parameters by yield line model is chord face failure, as is shown below on deformed shape of K joint of RHS after experiment and its cut.



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Geometry

of K shape joint of rectangular hollow section

Introduction

Failure mode meth.

General

❯ Joint parameters

Component method

Hollow to open

Assessment I

CBFEM

Principles

Validation

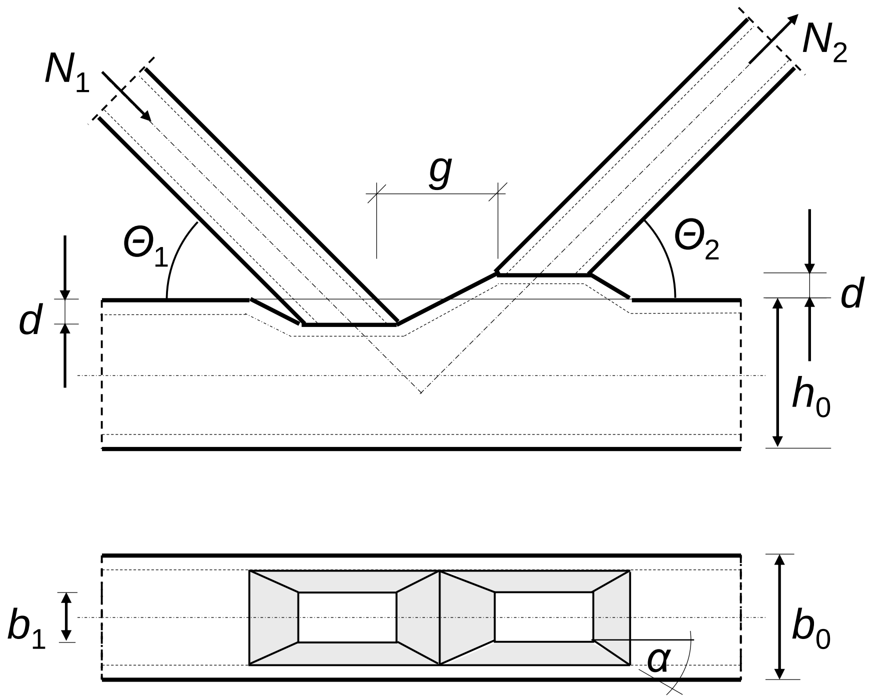
Verification

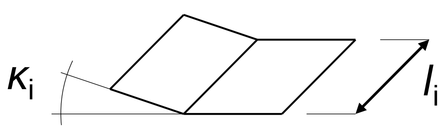
Benchmark case

Assessment II

Summary

- In principle,
  the yield line model
  is an upper bound
  approach





- Various yield line pattern have to be examined
  in order to obtain the lowest capacity
- Strain hardening effects and membrane action
  not considered

Limits of application of Yield line model

For joints with

- small β ratios

  the deformations may be too high to realise the yield line pattern

- medium β ratios

  the yield line model gives a good estimate of the chord face plastification capacity

- high β ratios

  prediction of an infinite strength

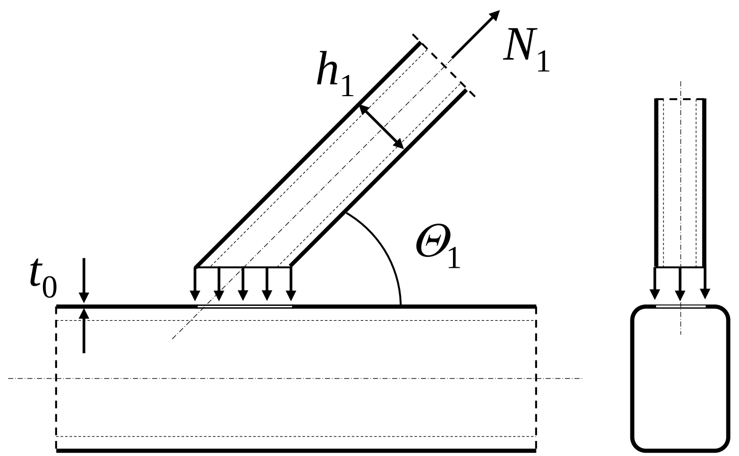
where β is the ratio of the mean diameter or width of the brace members, to that of the chord.
For T, Y and X joints it is

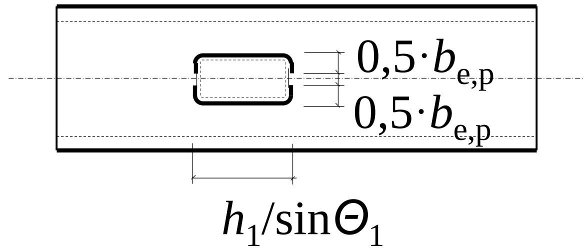
$$d_1/d_0;\ d_1/b_0 \text{ or } b_1/b_0.$$

brace diameter/chord diameter; brace diameter/chord width or brace width/chord width

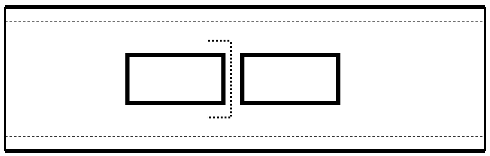
Geometry of punching shear model

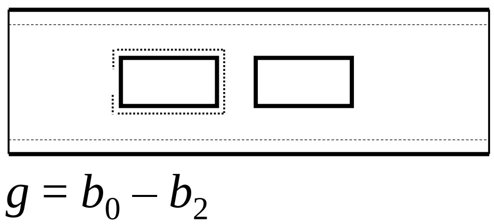
for the influencing joint parameters



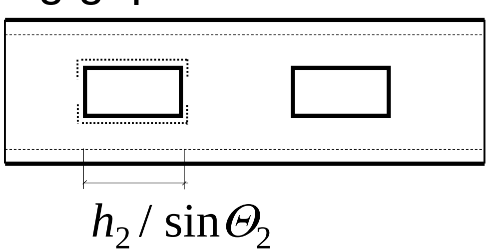


Very small gap





Big gap



Punching shear model

for the influencing joint parameters

- Punching shear is caused by the brace load component perpendicular to the chord face.
- Since of the non-uniform stress distribution at connection and not sufficient deformation capacity may be available, only parts of connection perimeters are effective for punching shear failure.
- Therefore the punching shear criterion is

$$N_1 = \frac{f_{y0}}{\sqrt{3}} t_0 \left(\frac{2h_1}{\sin\Theta_1} + 2b_{e,p} \right) \frac{1}{\sin\Theta_1}$$

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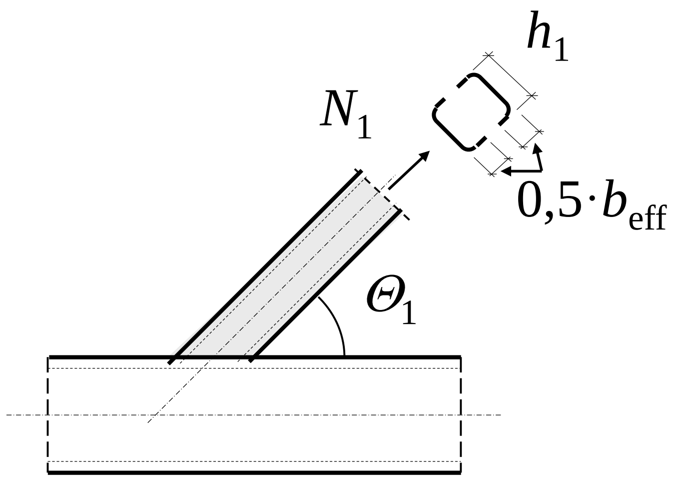
Brace effective width model
for the influencing joint parameters

- Similar to punching shear failure but the complete brace load has to be taken into account.
- For a T, Y and X joint, the effective width criterion is

$$N_1 = f_{y1}\, t_1\, (2h_1 + 2b_e - 4t_1)$$



- As for punching shear failure the gaps are important for the effective lengths.

Brace effective width model

for the influencing joint parameters

- For K-joints with gaps in the allowed range the brace effective width criterion is

$$N_2 = f_{y2}\, t_2\, (2h_2 + b_2 + b_e - 4t_1)$$

- No regulations for small gaps available
- For big gaps the criterion for T-, Y- and X-joints can be used

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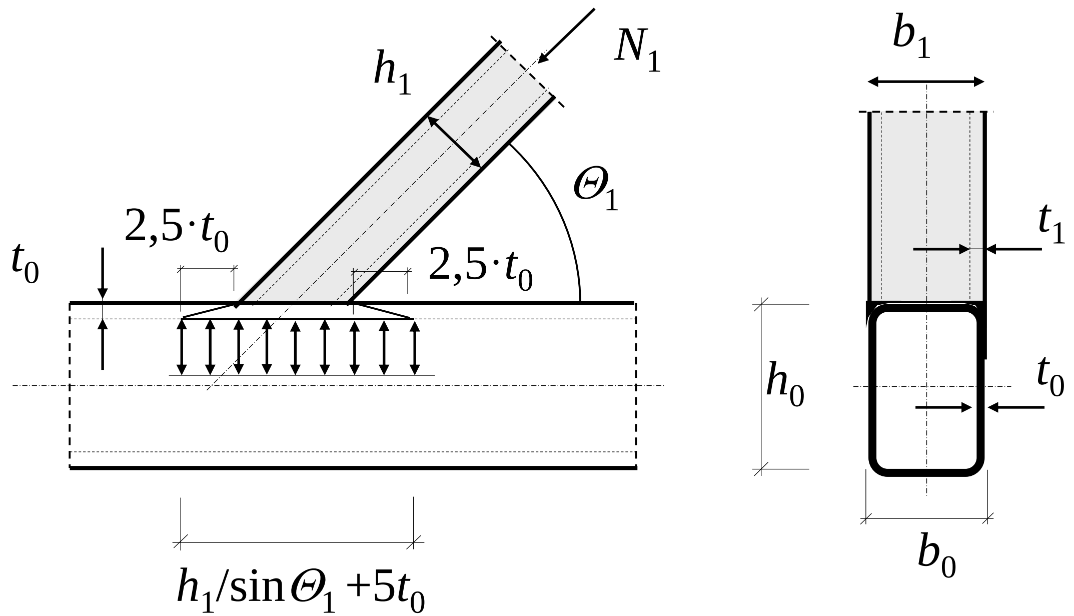
Chord side wall bearing/buckling model for the influencing joint parameters

- T, Y and X joints with a high β ratio generally fail by yielding or buckling of the chord side walls.

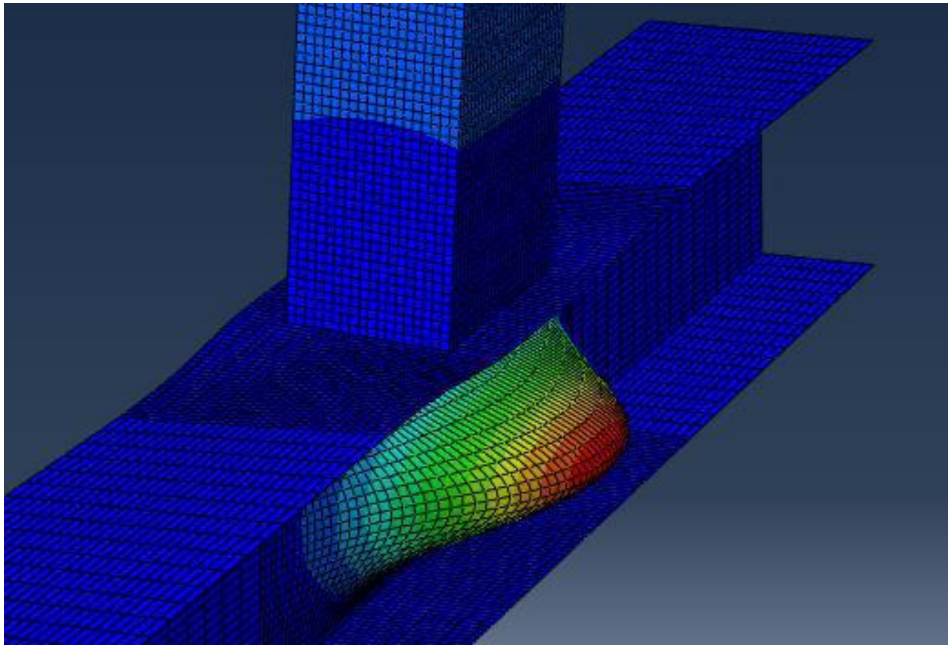


- For joints with $\beta = 1{,}0$ the yield capacity of the chord webs is determined as

$$N_1 = 2f_{y0} \cdot t_0 \left(\frac{h_1}{\sin\Theta_1} + 5t_0 \right) \cdot \frac{1}{\sin\Theta_1}$$

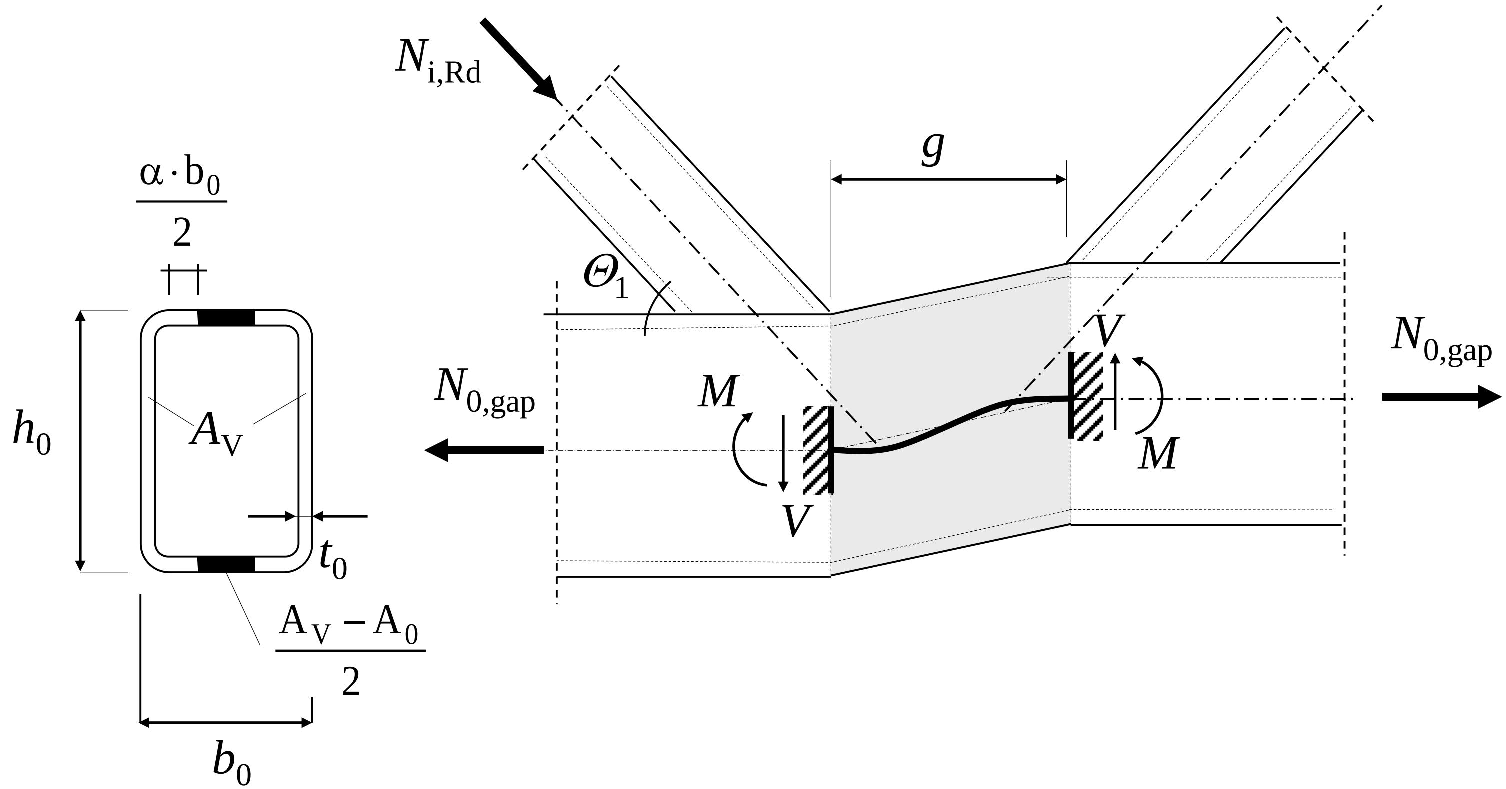
Chord side wall bearing/buckling model for the influencing joint parameters

- For slender walls the yield stress f_{y0} is replaced by a buckling stress f_k which is obtained from the European buckling curve *a*
- For a Euler strut with a buckling length of $h_0 - 3t$



Chord shear model

for the influencing joint parameters



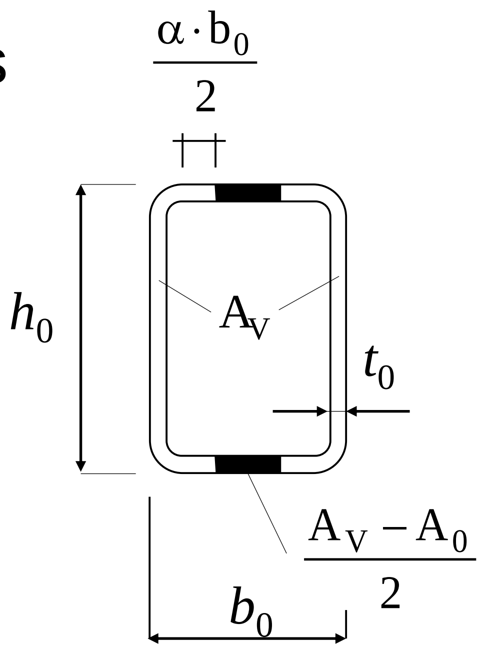
- Resistance is calculated
  based on the basic formulae for plastic design.

Chord shear model

for the influencing joint parameters

- The plastic shear load capacity is

$$V_{pl} = \frac{f_{y0}}{\sqrt{3}} \cdot A_V$$



with an effective shear area

$$A_V = (2h_0 + \alpha \cdot b_0)\, t_0$$

- Based on the Huber Hencky-Von Mises criterion the following interaction formula for shear resistance of the chord web

$$N_{o.gap} \leq (A_0 - A_V)\, f_{y0} + A_V\, f_{y0} \sqrt{1 - \left(V_{Sd} / V_{pl} \right)^2}$$

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Component based approach for hollow section joints

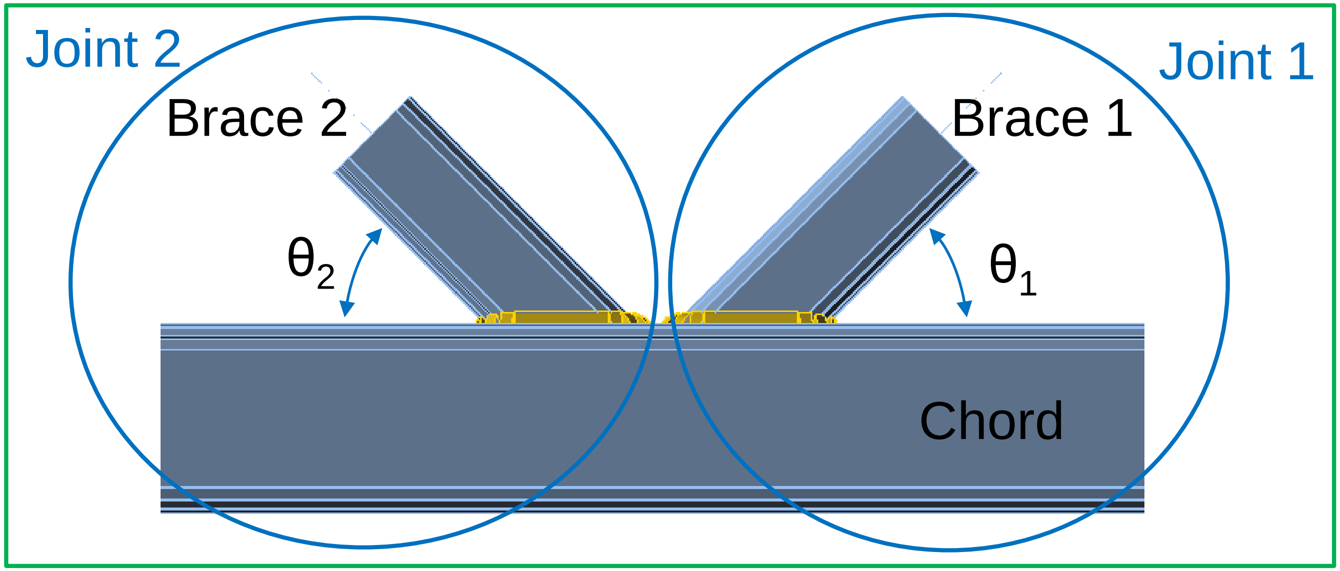
Lecture 2

Joint of hollow to open section

Principle

- Component based approach for hollow section design is formal reorganisation of equations to be engineering user friendly.
- Failure modes are represented as components.
- The same equations are used by curve fitting approach but in different formulation.

Joint configuration



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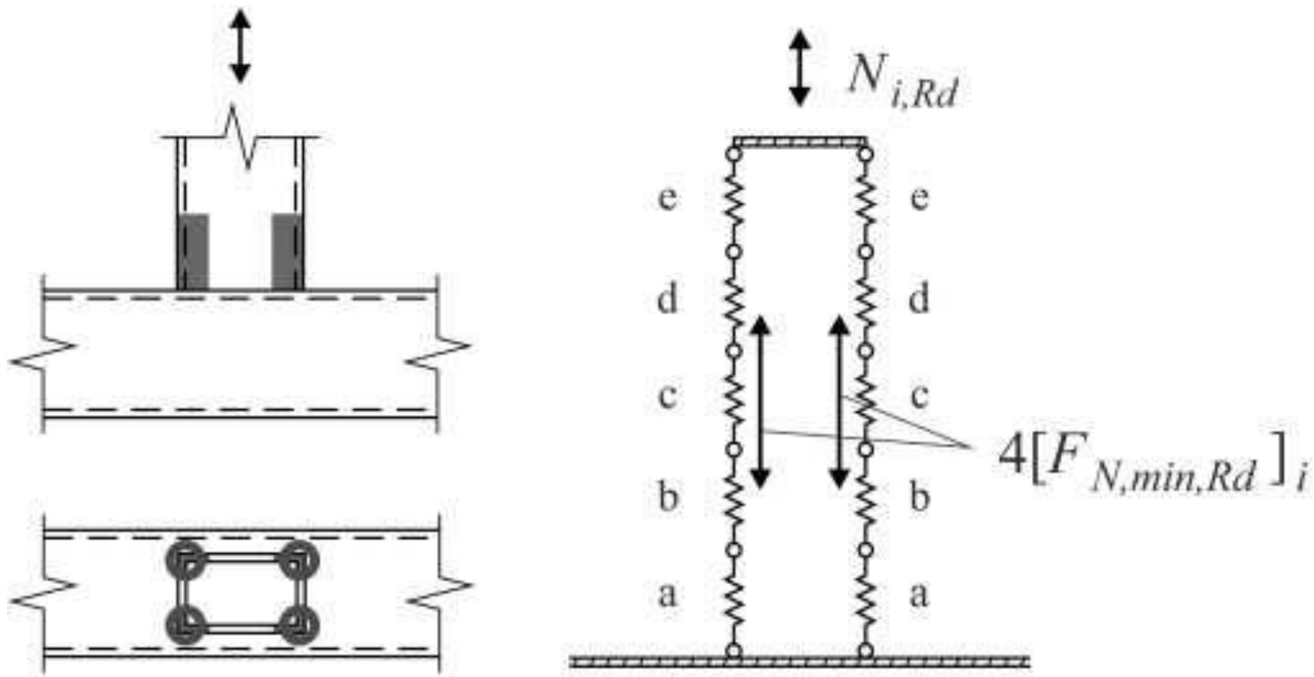
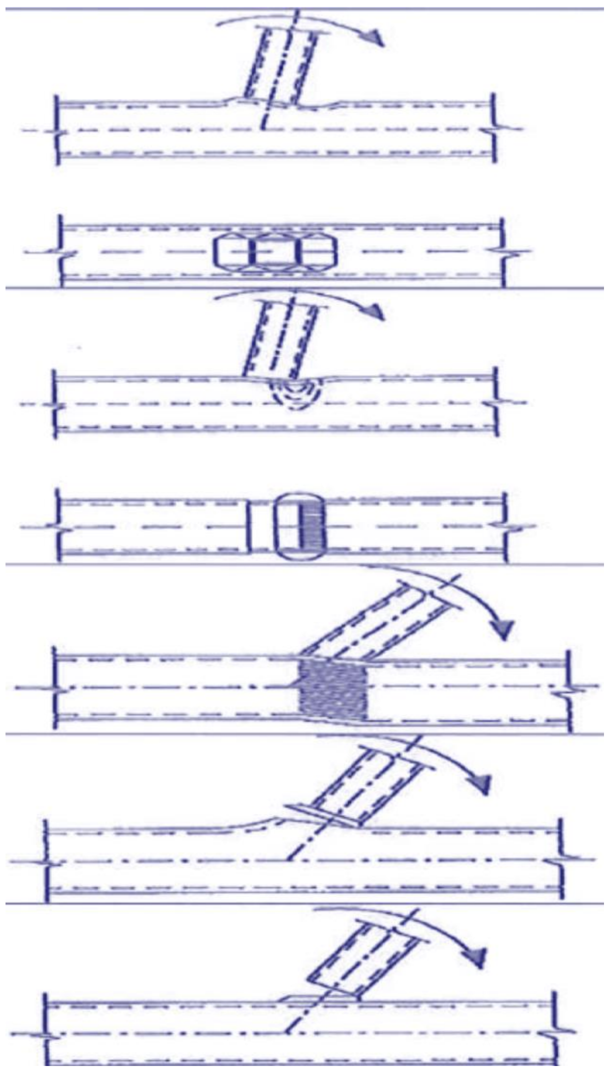
Defined lever arms and components (failure modes)

- k_{fa} factors transferred to
  - b_{eff} effective widths
  - r_a lever arm
- The interaction of load limits the application.



7 failure modes are modelled as 7 components



- Chord face in bending
- Chord side wall in tension/ compression
- Chord side wall in in shear
- Chord face under punching shear
- Brace flange and web in tension/compression

Application of principles to hollow to open joints

Lecture 2

Joint of hollow to open section

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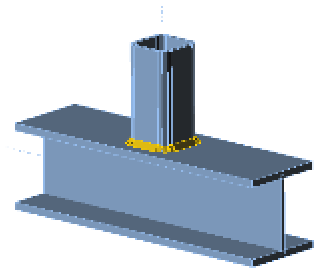
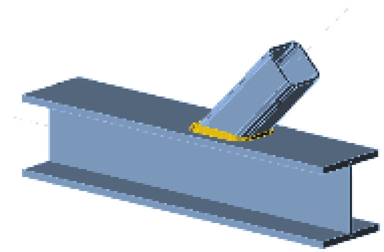
Hollow to open joints

as example of application

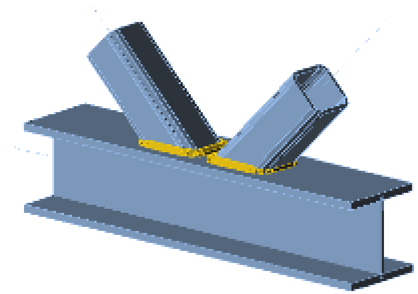
- Types of joint available in failure mode method
  - T, Y, X, K and K gap joint
- Two failure modes only
  - Brace failure
  - Chord web failure
  - Chord shear failure (only for K joint)
- Range of validity
  - Class 1 and 2 with limited flange width
- Influencing parameters
  - b_{eff} brace effective width
  - b_w chord web effective width



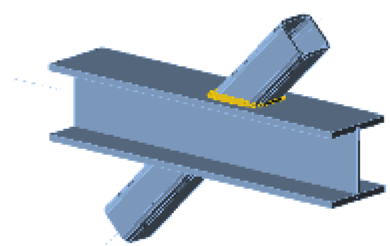
T joint



Y joint



K joint



X joint

Design resistance

of welded joints between RHS or CHS brace members and I or H section chords by failure mode method

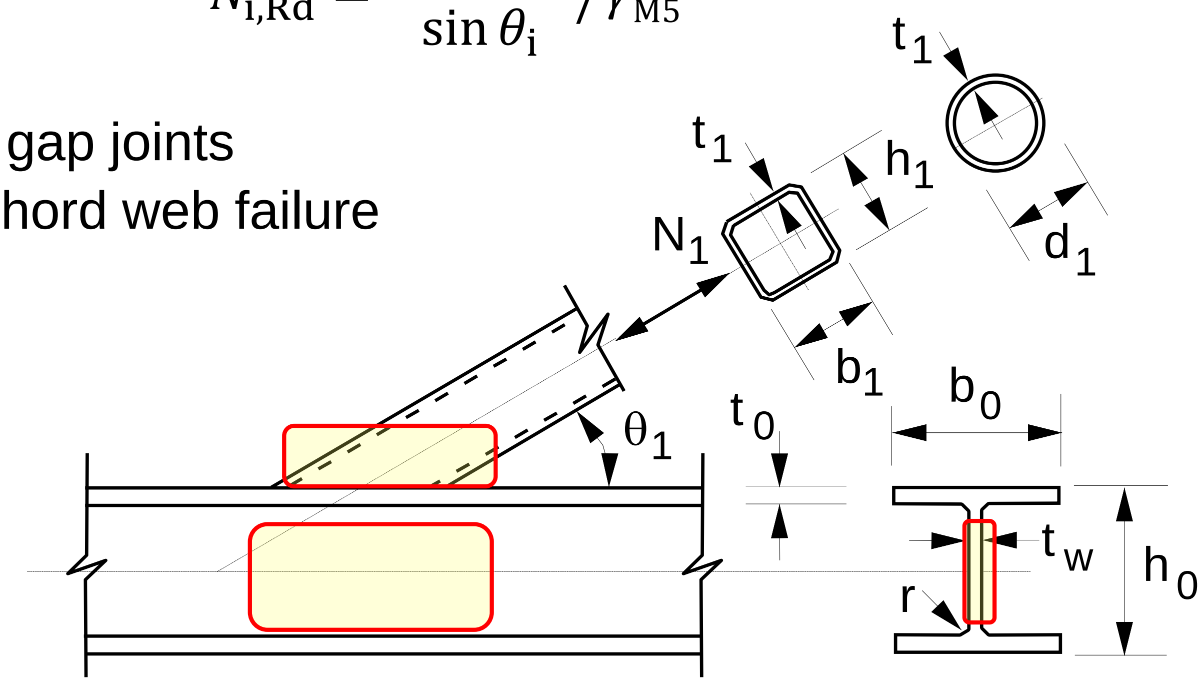
- Brace failure

$$N_{\mathrm{i,Rd}} = 2C_{\mathrm{f}} f_{\mathrm{yi}} t_{\mathrm{i}} b_{\mathrm{eff}} / \gamma_{\mathrm{M5}}$$

- Chord web failure

$$N_{\mathrm{i,Rd}} = \frac{f_{\mathrm{y0}} t_{\mathrm{w}} b_{\mathrm{w}}}{\sin \theta_{\mathrm{i}}} / \gamma_{\mathrm{M5}}$$

- For K gap joints
  also chord web failure



Design resistance

of welded joints between RHS or CHS brace members and I or H section chords by failure mode method

Chord shear failure for K gap joints and for X joints with $\cos\theta_\mathrm{i} > h_\mathrm{i}/h_0$ use $\alpha = 0$

$$N_{\mathrm{i,Rd}} = \frac{f_{\mathrm{y0}} A_{\mathrm{V,0,gap}}}{\sqrt{3}\sin\theta_\mathrm{i}} / \gamma_{\mathrm{M5}}$$

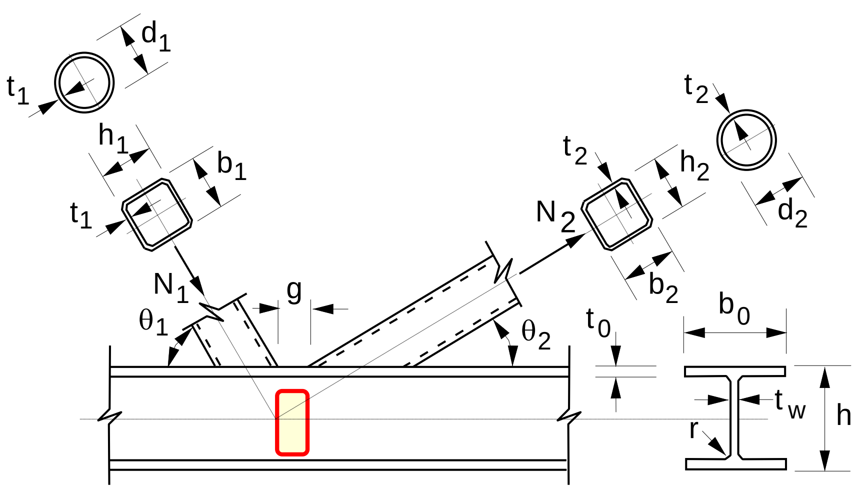
$$N_{\mathrm{0,gap,Rd}} = \left[\left(A_0 - A_{\mathrm{V,0,gap}}\right) f_{\mathrm{y0}} + A_{\mathrm{V,0,gap}} f_{\mathrm{y0}} \sqrt{1 - \left(\frac{V_{\mathrm{0,gap,Ed}}}{V_{\mathrm{0,gap,pl}}}\right)^2}\, \right] / \gamma_{\mathrm{M5}}$$

$$A_{\mathrm{V,0,gap}} = A_0 - (2-\alpha) b_0 t_0 + (t_\mathrm{w} + 2r) t_0$$

$$\alpha = \sqrt{\frac{1}{1 + (4g^2)/(3t_0^2)}}$$

$$V_{\mathrm{0,gap,pl}} = \frac{f_{\mathrm{y0}}}{\sqrt{3}} A_{\mathrm{v,0,gap}}$$

$$V_{\mathrm{0,gap,Ed}} = \left(N_{\mathrm{i,Ed}} \sin\theta_\mathrm{i}\right)_{\max}$$



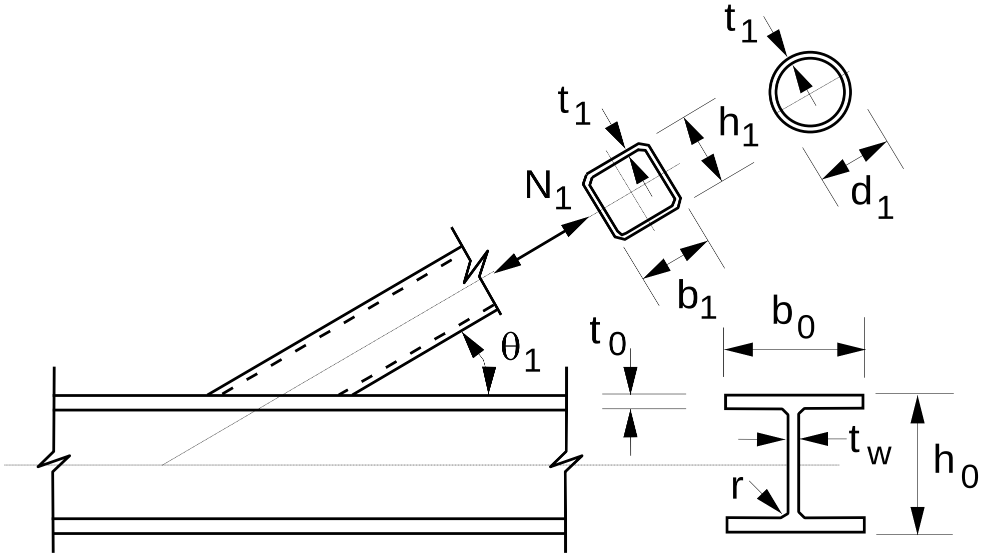
Effective width

of welded joints between RHS or CHS brace members and I or H section chords for failure mode method

For RHS braces

$$b_{\mathrm{eff}} = t_{\mathrm{w}} + 2r + 7t_0 \frac{f_{\mathrm{y0}}}{f_{\mathrm{yi}}} \quad \text{but} \leq b_{\mathrm{i}} + h_{\mathrm{i}} - 2t_{\mathrm{i}}$$

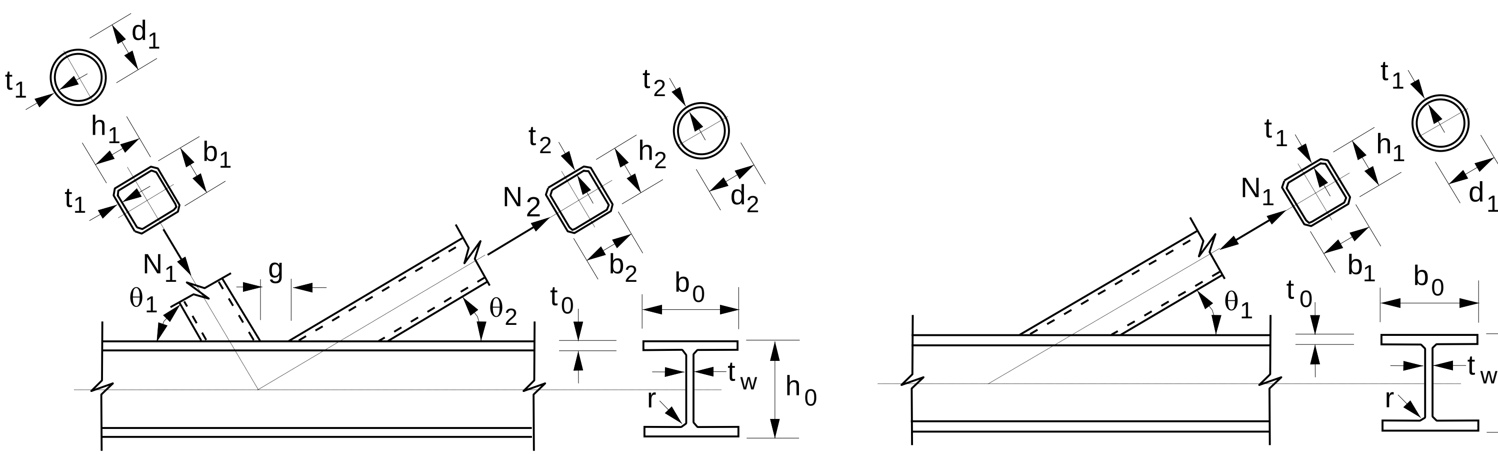
$$b_{\mathrm{w}} = \frac{h_{\mathrm{i}}}{\sin\theta_{\mathrm{i}}} + 5(t_0 + r) \quad \text{but} \leq \frac{2t_{\mathrm{i}}}{\sin\theta_{\mathrm{i}}} + 10(t_0 + r)$$



Range of validity

for welded joints between CHS or RHS brace members and I or H section chord members for failure mode method

Type of joint	Joint parameters					
	Chord web width d_w	b_i/t_i and h_i/t_I or d_i/t_i Compression	Tension	h_i/b_i	b_0/t_0	Gap
X	Class 1 and $d_w \le 400$ mm	Class 1 or 2 and $\frac{h_i}{t_i} \le 35$ $\frac{b_i}{t_i} \le 35$ $\frac{d_i}{t_i} \le 50$	$\frac{h_i}{t_i} \le 35$ $\frac{b_i}{t_i} \le 35$ $\frac{d_i}{t_i} \le 50$	$0{,}5 \le h_i/b_i \le 2{,}0$	Class 1 or 2	–
T or Y	Class 1 or 2 and $d_w \le 400$ mm					
K gap						$g \ge t_1 + t_2$



Component approach

of welded joints between RHS or CHS brace members and I or H section chords by failure mode method

Brace failure from failure mode method

$$N_{\mathrm{i,Rd}} = 2C_{\mathrm{f}} f_{\mathrm{yi}} t_{\mathrm{i}} b_{\mathrm{eff}} / \gamma_{\mathrm{M5}}$$

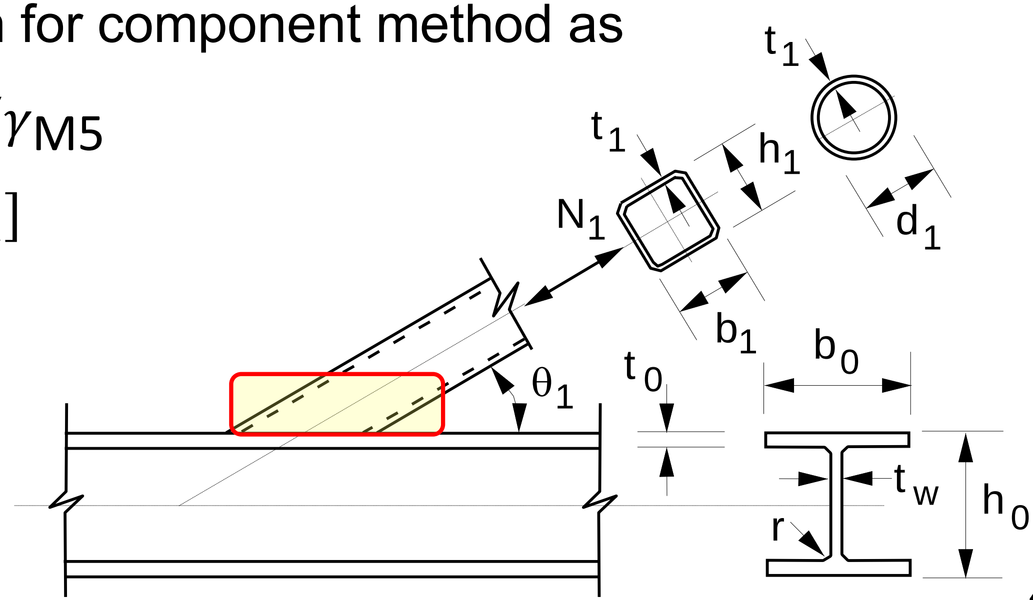
$$b_{\mathrm{eff}} = t_{\mathrm{w}} + 2r + 7t_0 \frac{f_{\mathrm{y0}}}{f_{\mathrm{yi}}} \quad \text{but} \leq b_{\mathrm{i}} + h_{\mathrm{i}} - 2t_{\mathrm{i}}$$

can be overwritten for component method as

$$F_{\mathrm{e,Rd}} = C_{\mathrm{f}} f_{\mathrm{yi}} t_1 b_{\mathrm{eff}} / \gamma_{\mathrm{M5}}$$

$$N_{\mathrm{1,Rd}} = 4[F_{\mathrm{N,min,Rd}}]$$

$$b_{\mathrm{eff},e} = 0{,}5 b_{\mathrm{eff}}$$



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Component approach

of welded joints between RHS or CHS brace members and I or H section chords by failure mode method

Chord web failure from failure mode method

$$N_{\mathrm{i,Rd}} = \frac{f_{\mathrm{y0}} t_{\mathrm{w}} b_{\mathrm{w}}}{\sin \theta_{\mathrm{i}}} / \gamma_{\mathrm{M5}}$$

$$b_{\mathrm{w}} = \frac{h_{\mathrm{i}}}{\sin \theta_{\mathrm{i}}} + 5(t_0 + r) \quad \text{but} \quad \leq \frac{2 t_{\mathrm{i}}}{\sin \theta_{\mathrm{i}}} + 10(t_0 + r)$$

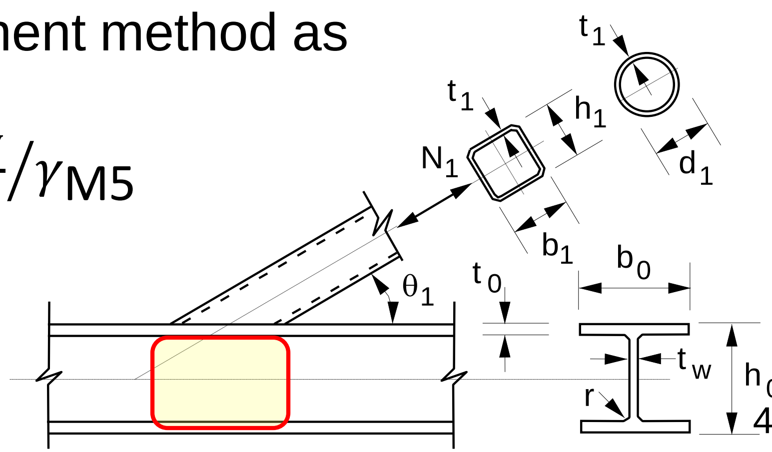
$$K_{\mathrm{N,ch,b}} = 1{,}0; K_{\mathrm{b,ch,b}} = 1{,}0; t_0 = t_w/2$$

can be overwritten for component method as

$$N_{\mathrm{1,Rd}} = 2\, K_{\mathrm{N,ch,b}} K_{\mathrm{N,ch,b}} \frac{f_{\mathrm{y0}} t_0 b_{\mathrm{w}}}{\sin \theta_{\mathrm{i}}} / \gamma_{\mathrm{M5}}$$

$$N_{\mathrm{1,Rd}} = 4[F_{\mathrm{N,min,Rd}}]$$

$$b_{\mathrm{eff},e} = b_w / \sin \theta_{\mathrm{i}}$$



Assessment I

- What limits the application of component method to hollow section joint design?
- How are applied the analytically derived parameters in failure mode design procedure?
- What failure modes are excluded and how?
- Why are used range of validity?
- Is the failure mode method the curve fitting one?
- What is the principle of component method prepared based on failure mode method?
- What failure modes may be observed at hollow to open section joints?

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Component Based Finite Element Method

Lecture 2

Joint of hollow to open section

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 taking into account the necking of the coupon during its yielding before rupture.

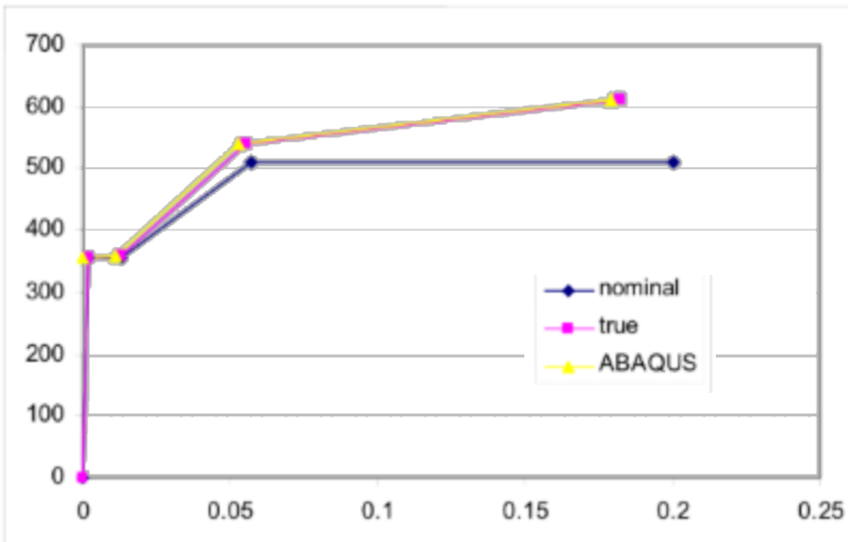

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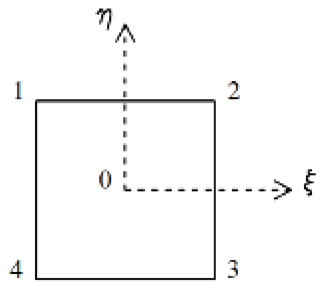
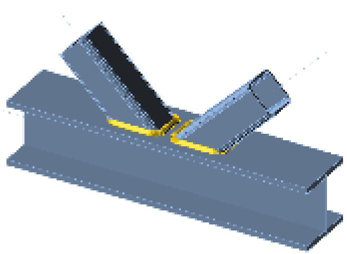
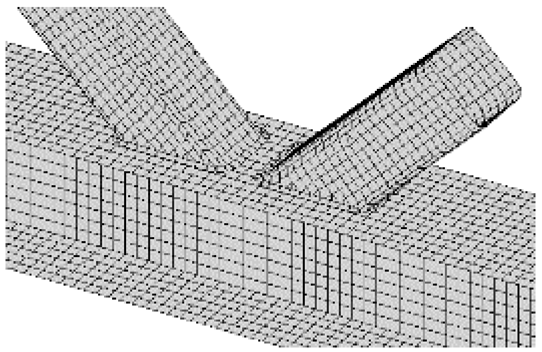
Plate and cross sections

- For modelling of plate are applied four node quadrangle shell elements with six degrees of freedom.
  I.e. there are three translations and three rotations in every node.



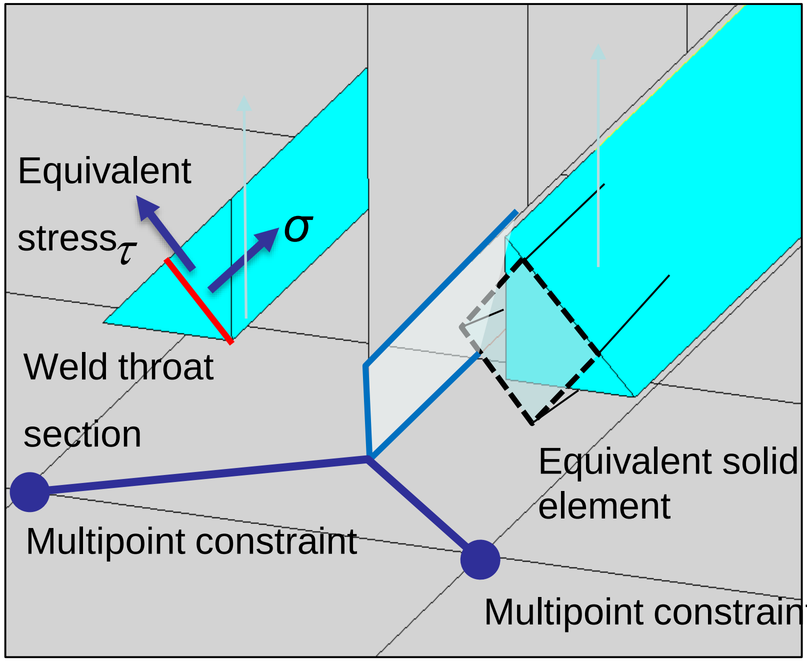
- The cross section is build from plates with independent meshes, which are connected by constraints, to simplify the meshing procedure.





Welds

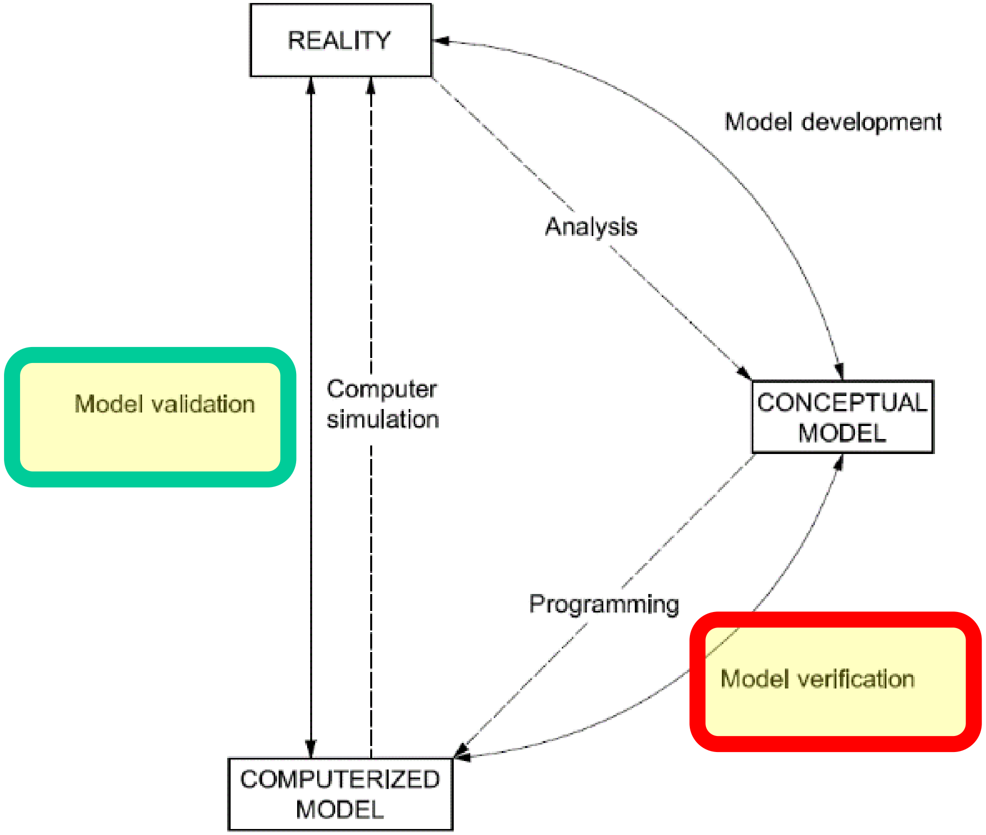
- Filled weld is modelled by equivalent solid elastoplastic element, which is added between plates to express the weld behaviour, see Fig. below.
- The element respects the weld throat thickness, position, and orientation to assure a good representation of weld deformation stiffness, resistance and deformation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



Wald et al. (2016)

Verification & Validation

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



ISO/FDIS 16730
Fire safety engineering - Assessment, verification and validation of calculation methods, Geneva, 2008.

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Design and research oriented model

Current approval of design models consist of

1) **Experiments**

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

2) **Validated** on experiments

3) Numerical experiments

- **Design numerical model** (DOFEM)

4) **Verified** to numerical experiments and/or another design models

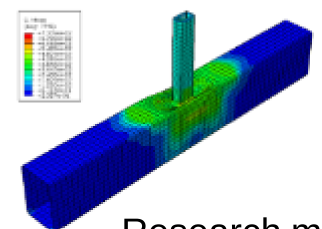
5) Sensitivity study

6) Validity range

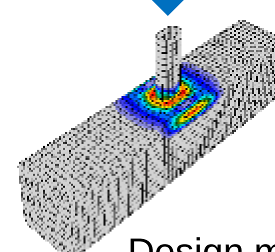
- **Benchmark case** (BC)

7) To help the users of model to check up its correctness and proper use

Experiment



Research model



Design model

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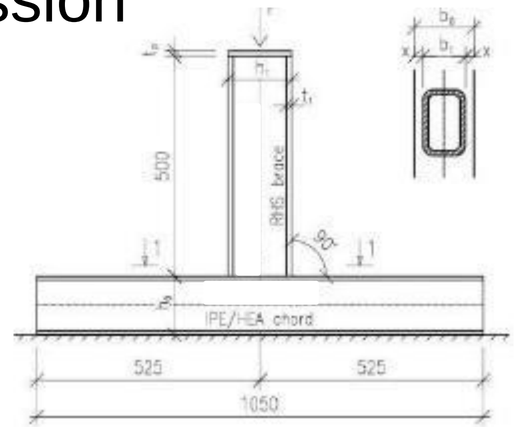
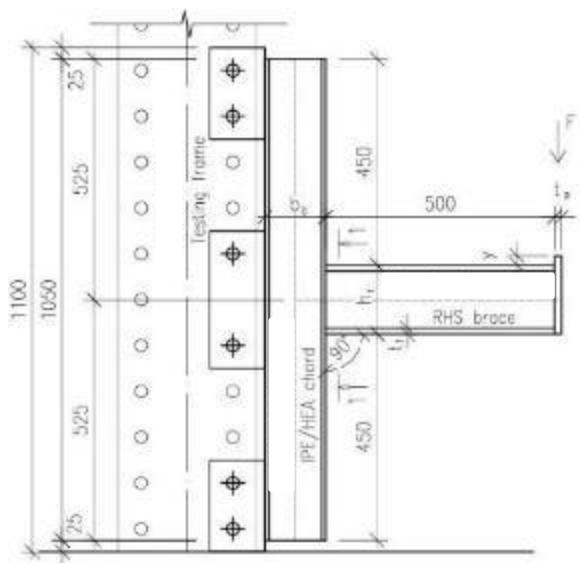
Experiments with T joint of hollow to open section

- In compression



- In bending



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Experiments in compression

- Geometry

Specimen number	Chord (mm)						Brace (mm)			
	b_0	h_0	t_f	t_w	r	L_0	h_1	b_1	t_2	L_1
A1	140	133	8,5	5,5	12	1050	150	100	12,5	500
A2	140	133	8,5	5,5	12	1050	150	100	5	500
A3	140	133	8,5	5,5	12	1050	80	140	4	500
A4	135	270	10,2	6,6	15	1050	150	100	12,5	500

- Failure modes

A3 - Brace failure

A1 - Chord web failure

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❯ Validation
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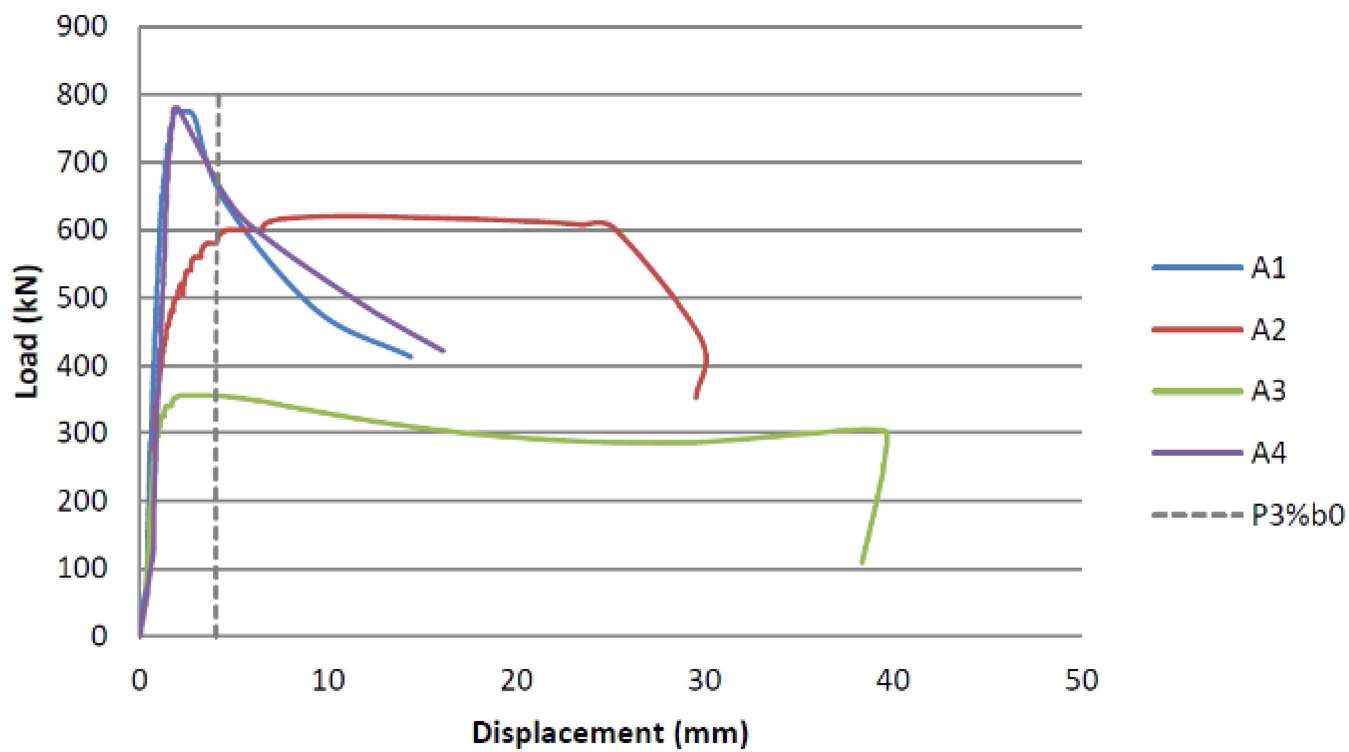
Summary

Results of experiments in compression

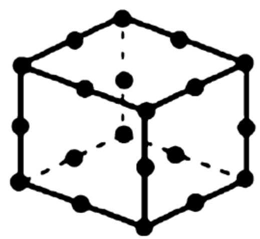
Resistance	A1	A2	A3	A4
Failure	Chord web	Brace	Brace	Chord web
$F_{peak\ load}$ [kN]	775,14	620,01	355,24	780,7
$F_{3\%b0}$ [kN]	643,99*	590,04	354,60	644,23
$F_{\varepsilon\ 5\%}$ [kN]	646,08	540,36	324,83	685,2

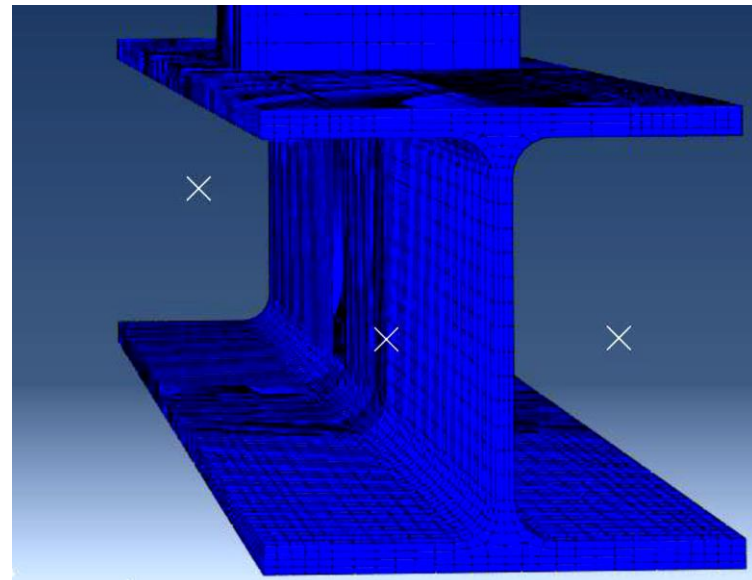
** decreasing load after reaching the peak load*



Research oriented FEM

- ABAQUS 6.13
- Solid quadratic element (20-node brick, C3D20)



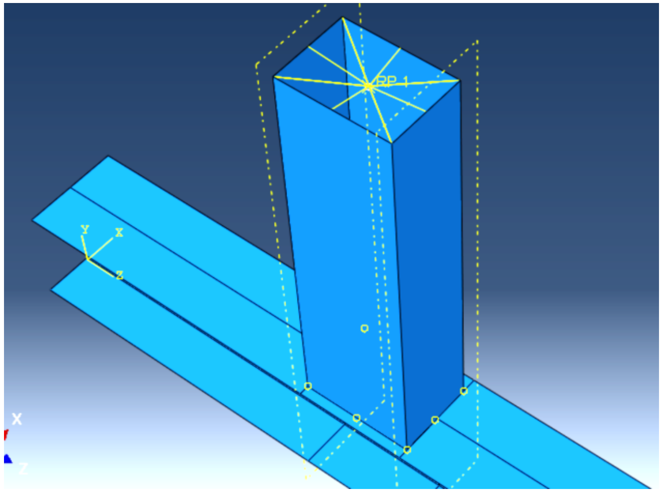


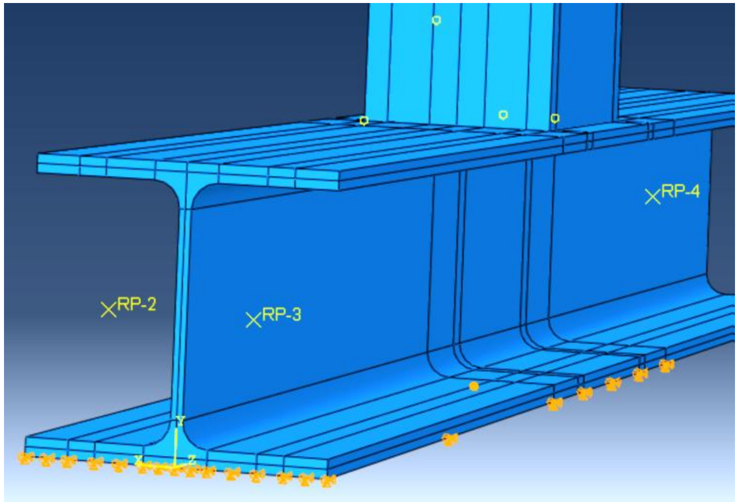
- True stress-strain multilinear material model

HEA140		IPE270		RHS150X100X5		RHS150X100X12.5		RHS140X80X4	
σ_{true} [MPa]	$\varepsilon_{plas,true}$	σ_{true} [MPa]	$\varepsilon_{plas,true}$	σ_{true} [MPa]	$\varepsilon_{plas,true}$	σ_{true} [MPa]	$\varepsilon_{plas,true}$	σ_{true} [MPa]	$\varepsilon_{plas,true}$
0	0	0	0	0	0	0	0	0	0
386,44	0	448,36	0	519,89	0	579,93	0	357,84	0
389,92	0,009	452,45	0,009	524,54	0,009	583,57	0,006	361,59	0,010
601,86	0,060	603,43	0,046	580,85	0,028	675,93	0,034	538,71	0,054
678,36	0,179	689,40	0,179	676,20	0,179	781,56	0,179	611,04	0,179

Boundary conditions for research oriented FEM

- Bottom flange boundary condition
  - Rotation and translation restrain in all axis
- Load point
  - Coupling to top of braces edges





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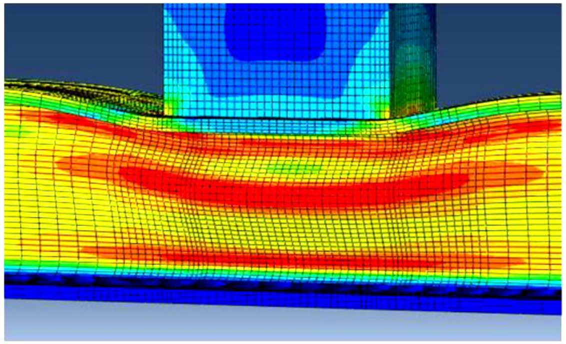
Validation of failure modes

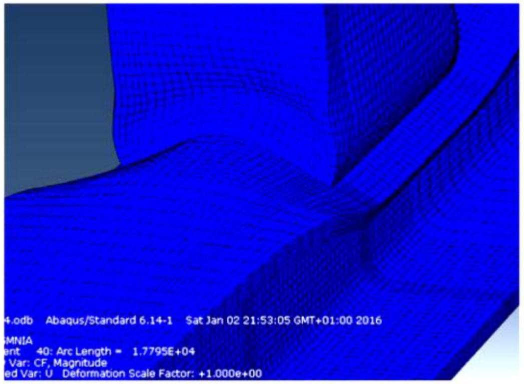
- Both failure modes were well predicted

Resistance	A1	A2	A3	A4
Failure	Chord web	Brace	Brace	Chord web
$P_{peak\ load}$ [kN]	775,14	620,01	355,24	780,71
$P_{3\%b0}$ [kN]	643,99*	590,04	354,60	644,23*
$P_{\varepsilon\ 5\%}$ [kN]	646,08	540,36	324,83	685,24

- Failure of chord web, experiment A1



- Failure of brace, experiment A2



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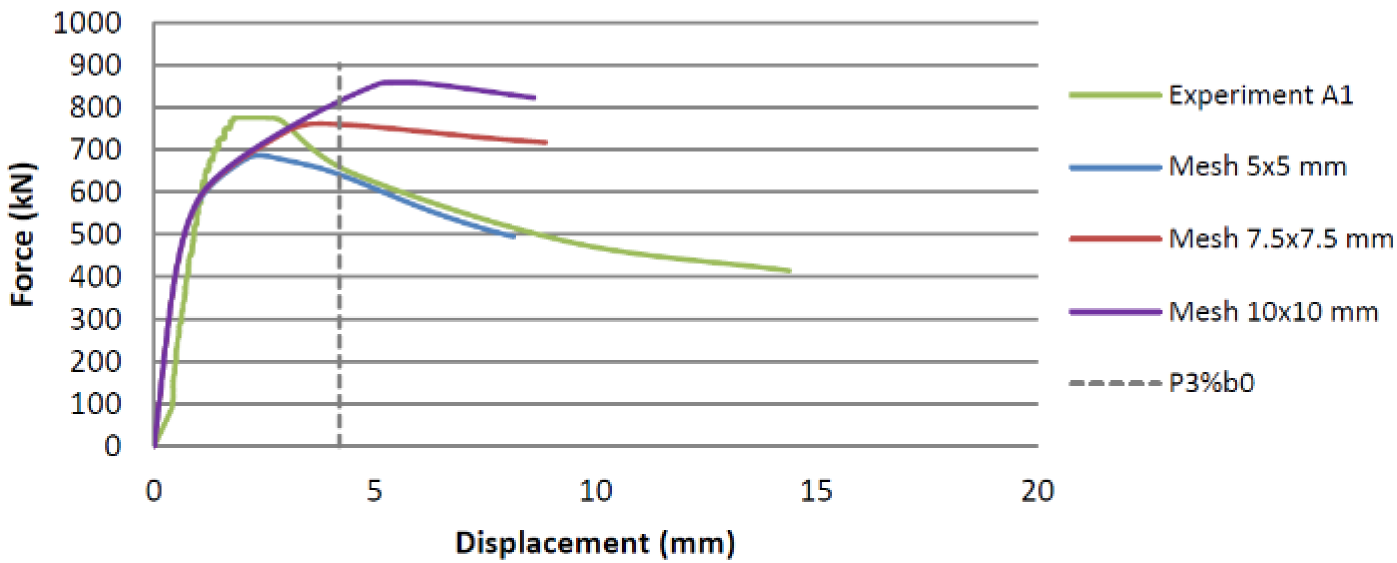
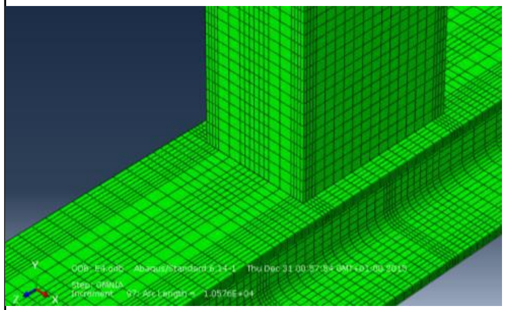
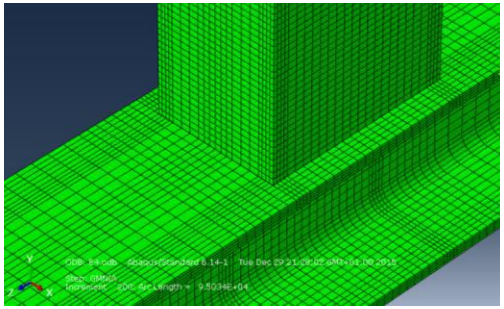
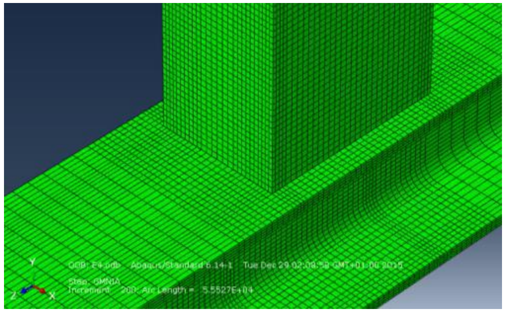
Mesh sensitivity study

- The Figure below shows the importance of the mesh size to the prediction of behaviour of joint





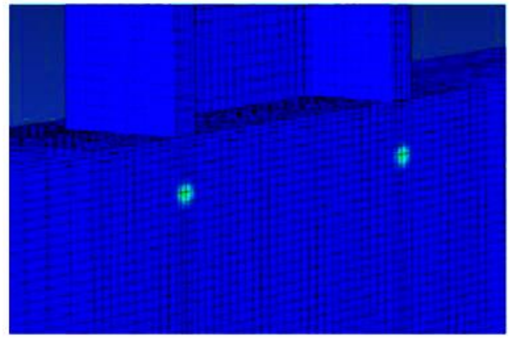


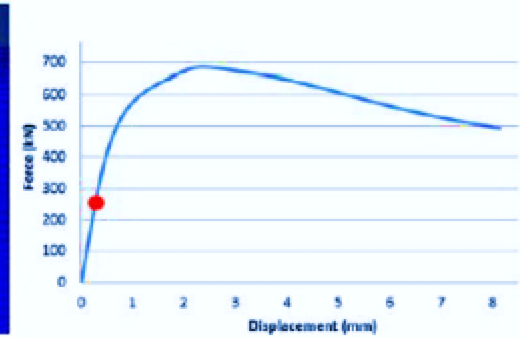


Description of local and global behaviour

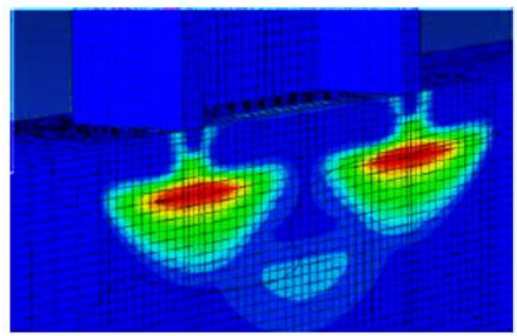
Development of plastic zones

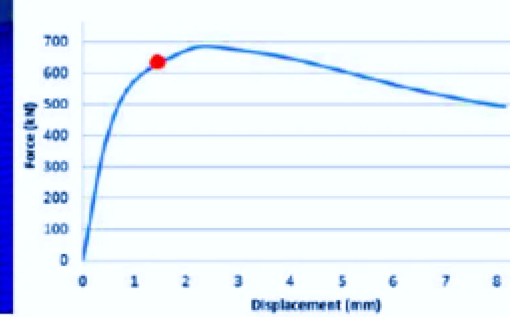
- The first yielding in the chord web



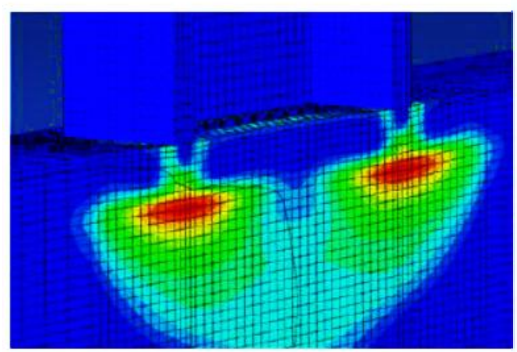


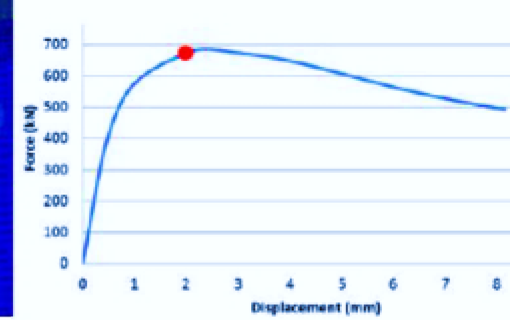
- 5% strain





- Full plasticity at the peak load





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Quality of prediction of resistance

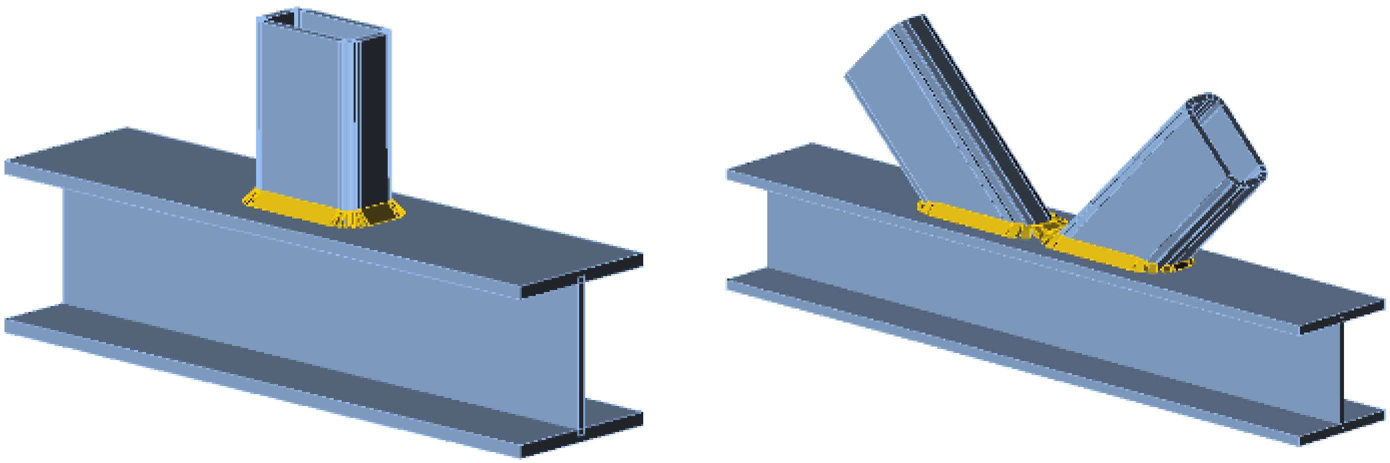
- The validation should answer the quality of prediction on global behaviour namely in important points of design.
- Table below shows the prediction of resistance by deformation of upper surface $b_0/300$ (used by curve fitting models) and 5% of strain (used by numerical models) for experiment in compression A1 with failure of chord web.

	Experiment A1	ROFEM	%
$P_{peak\ load}$ (kN)	775,1	686,0	**12%**
$P_{5\%\ strain}$ (kN)	646,1	683,9	**6%**
$P_{3\%b0}$ (kN)	620,3	638,3	**3%**

Verification of T-joint and K-joint

CBFEM model to failure mode procedure

- A uniplanar T-joint and K-joint of a rectangular hollow section brace to an open section chord.
- The brace section is RHS 140x70x10.
- The chord sections are IPE, IPN, HEA a HEB.
- The brace is loaded in tension/compression or by in-plane bending moment.



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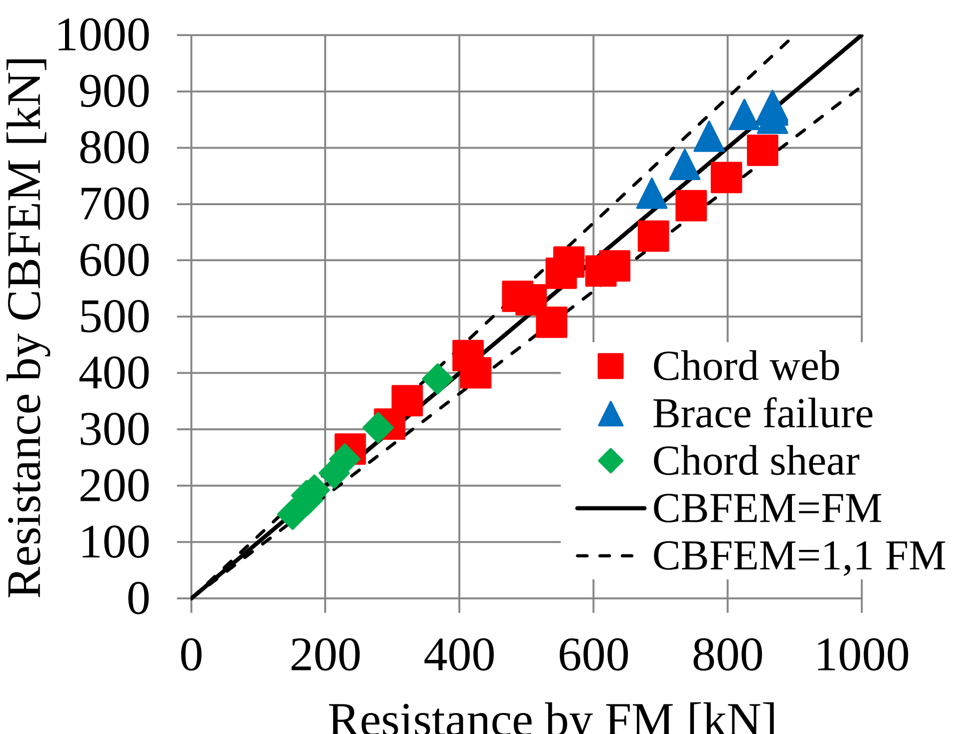
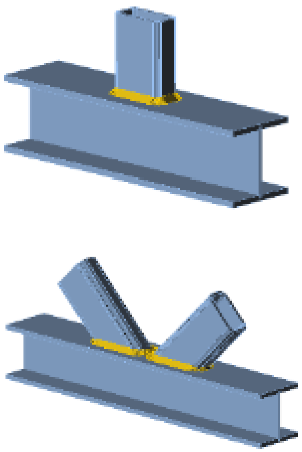
Verification of T-joint and K-joint in compression

- The prediction by component based finite element method (CBFEM) is verified with the failure modes (FM) implemented in EN 1993-1-8:2005.
- Three failure modes occur in joints of the welded rectangular hollow sections to the open sections, e.g. the local yielding of brace (brace failure), the chord web failure and the chord shear.





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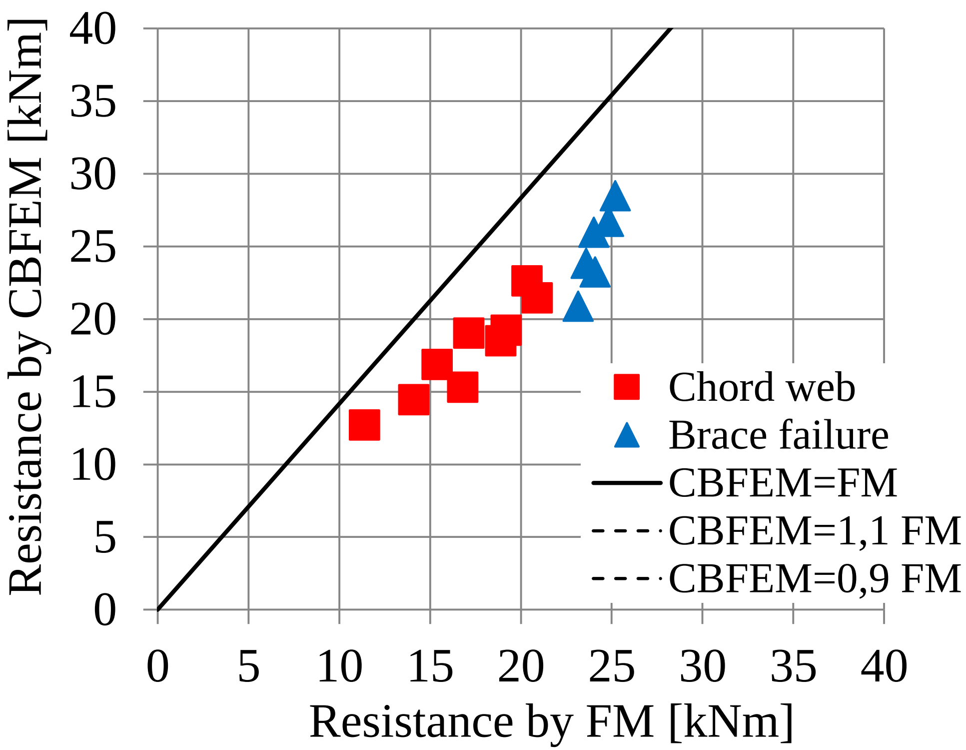
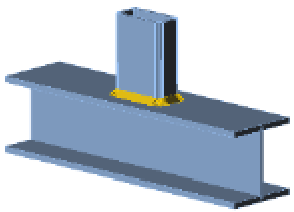
Verification of T-joint in bending

- The prediction by component based finite element method (CBFEM) is verified with the failure modes (FM) implemented in EN 1993-1-8:2005.
- Two failure modes occur in joints of the welded rectangular hollow sections to the open sections, e.g. the local yielding of brace (brace failure) and the chord web failure.

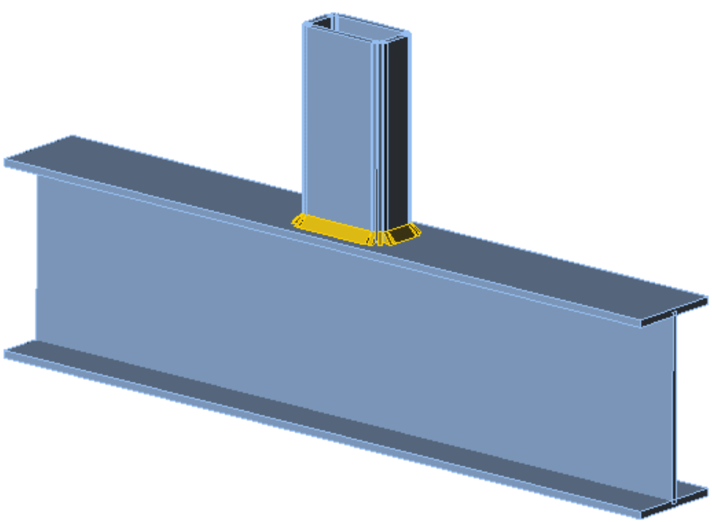


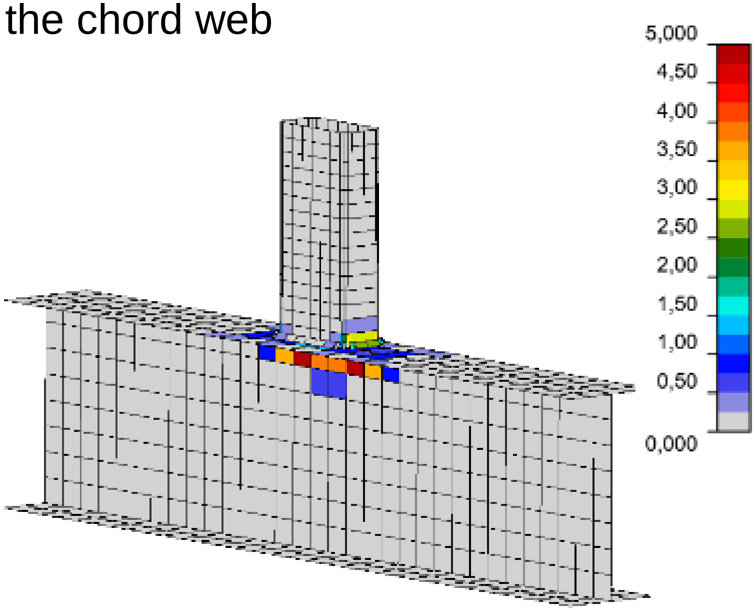


Benchmark case

Uniplanar T-joint between RHS brace and I chord

- **Input**
  - Chord: IPE270, Steel S235
  - Brace: RHS 140x70x10, Steel S235
  - Weld: Throat thickness a_w = 10 mm, Fillet weld around the brace
- **Output**
  - Design resistance in compression/tension $F_{c,Rd}$ = 431 kN
  - Collapse mode is full yielding of the chord web





Plastic strain [%]

Assessment II

- How is modelled the material for research and how for design models?
- What elements are recommended for plates?
- How are modelled welds?
- What is expected to be the accurate solution in mesh sensitivity study?
- How differs validation from verification?
- What are two major purposes of benchmark cases in application of FEA analyses?

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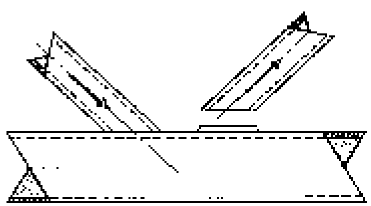
Summary

Lecture 2

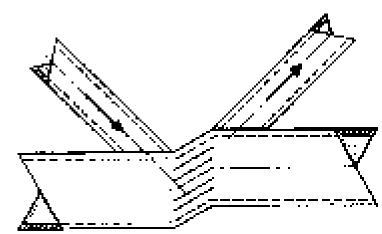
Joint of hollow to open section

Summary

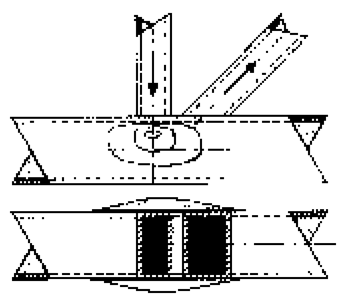
- The hollow sections to open sections joints belongs to family of hollow section joints.
- There are three failure modes
  - Brace failure
  - Chord web failure
  - Chord web shear failure in case of gap



Brace failure



Shear failure of the chord



Chord web failure

Summary

- The curve fitting methods are used for evaluation of design resistances by each possible failure mode.
- Range of validity limits application of expressions to experimentally approved solutions only.
- Component based approach is for design of some rectangular hollow sections great simplification.
- For design of circular hollow sections brings unpleasant complexity.
- For complex joints generally loaded can not be used.

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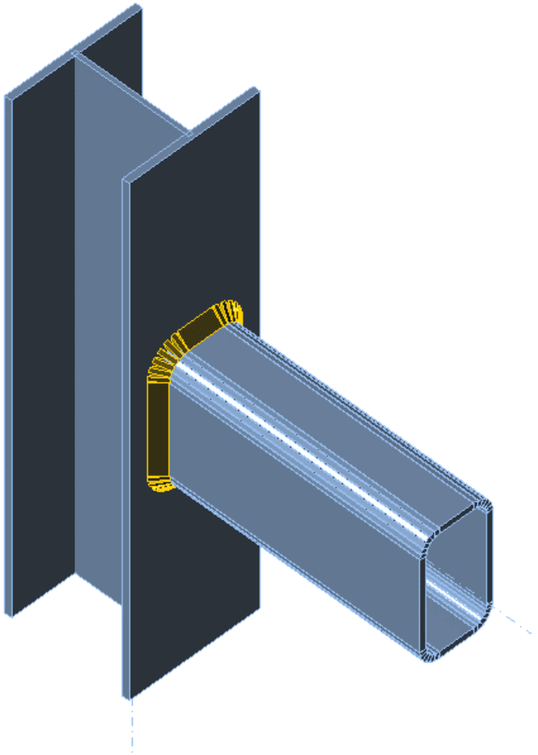
Prediction of global and local behaviour

T joint of RHS brace and HEA chord

- Chord HEA180
- Brace RHS 180x100x8.8
- Steel S355
- Weld throat thickness 11 mm



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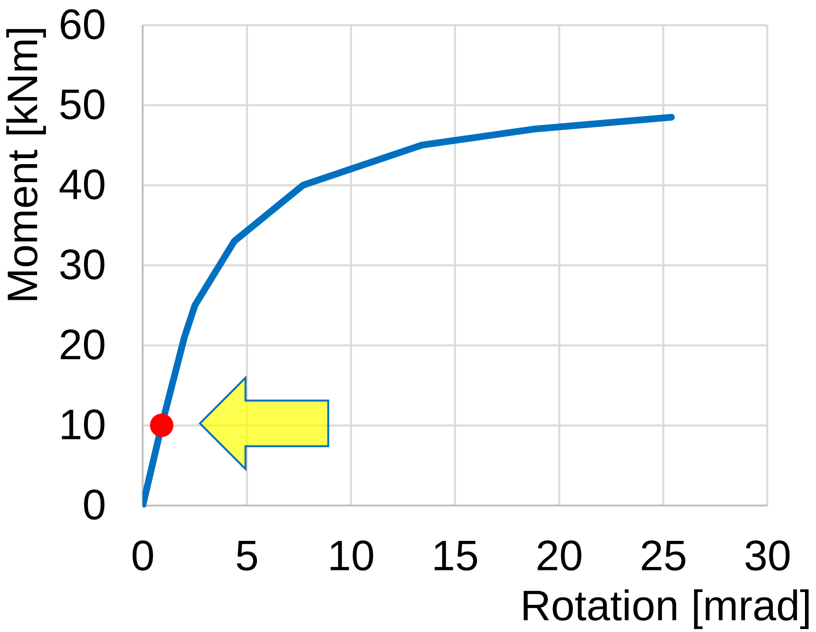
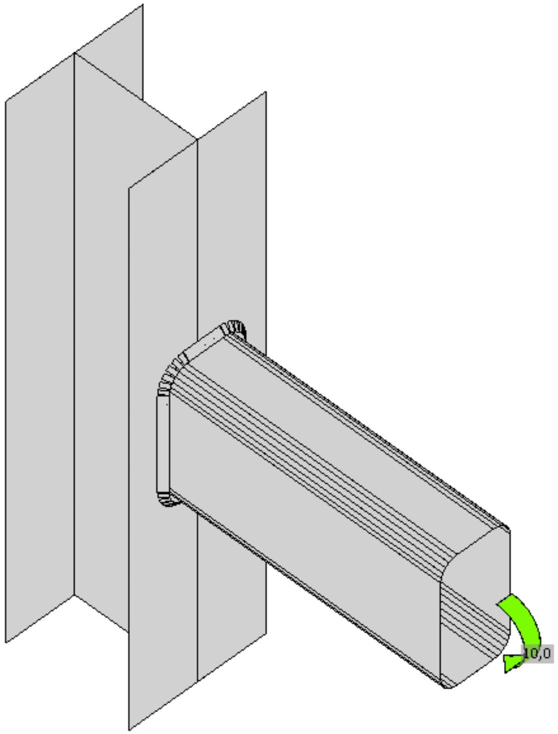
Global and local behaviour

Elastic stage





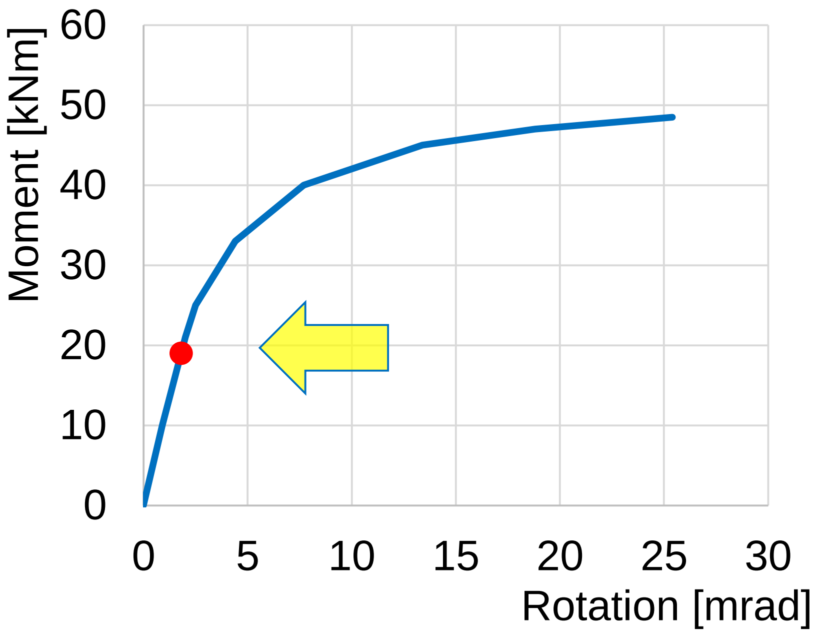
M = 10 kNm

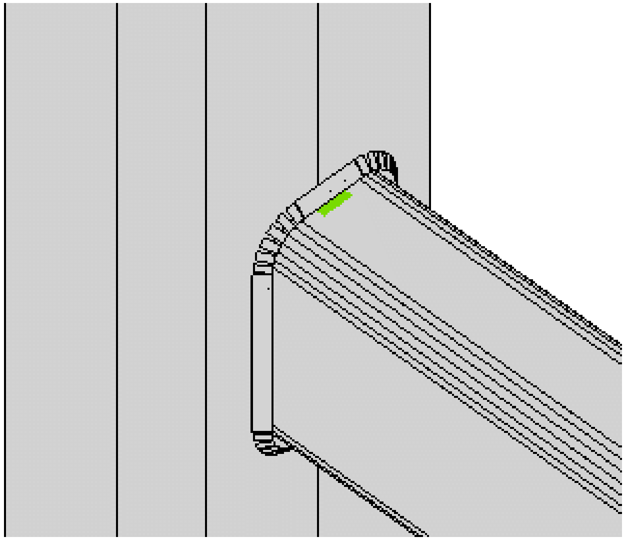
φ = 0,9 mrad

S_j = 10,7 MNm/rad

Global and local behaviour

Plastification of the upper flange of RHS brace





M = 19 kNm

φ = 1,8 mrad

S_j = 10,7 MNm/rad

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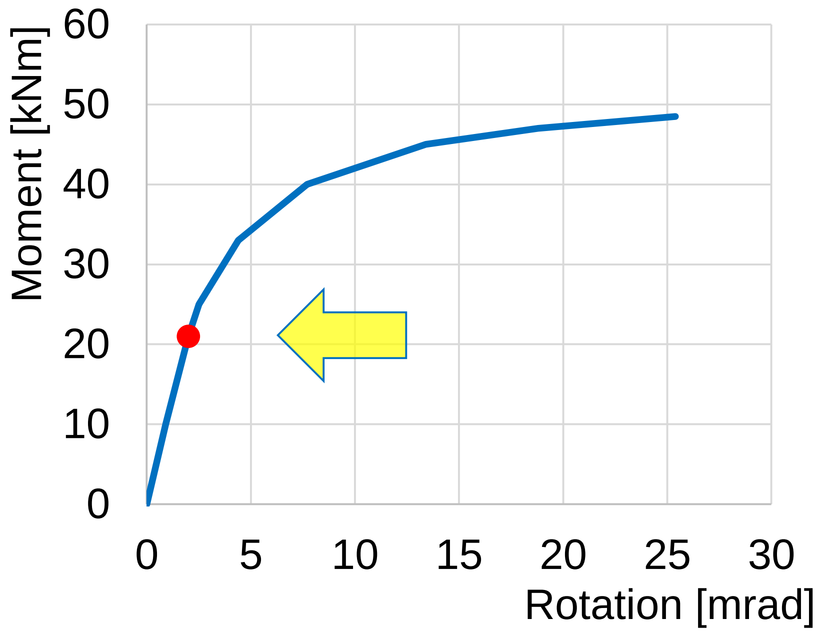
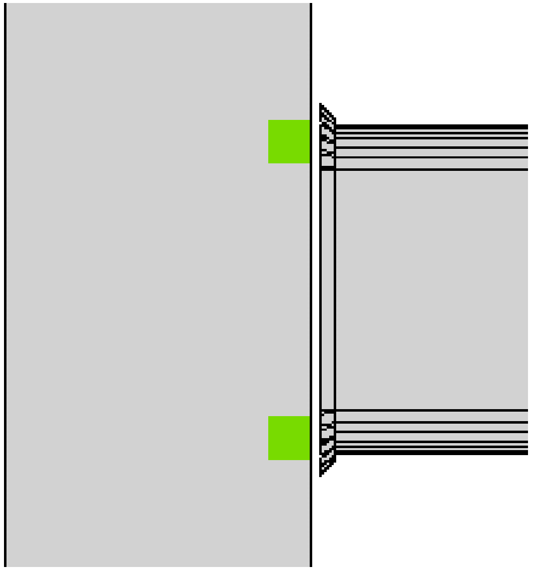
Global and local behaviour

Initial plastification in the open section web





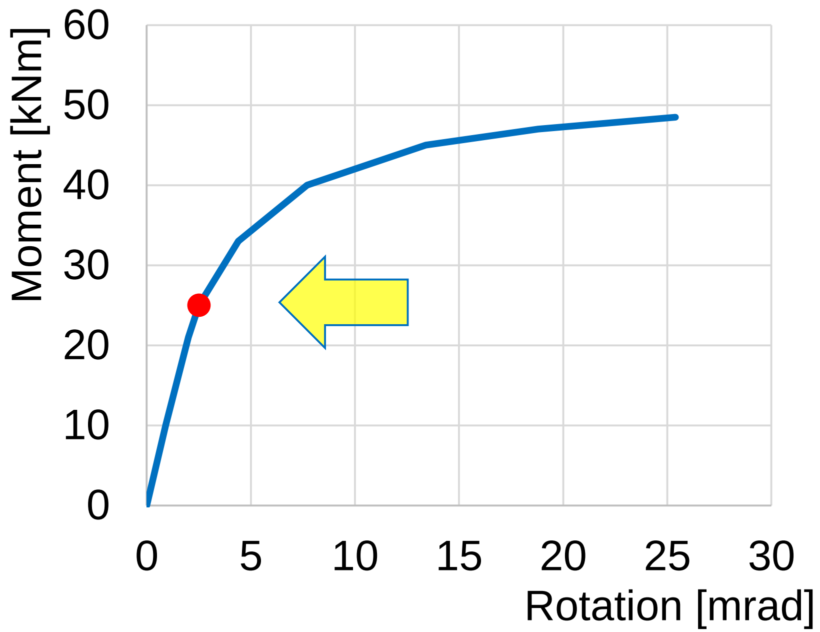
M = 21 kNm

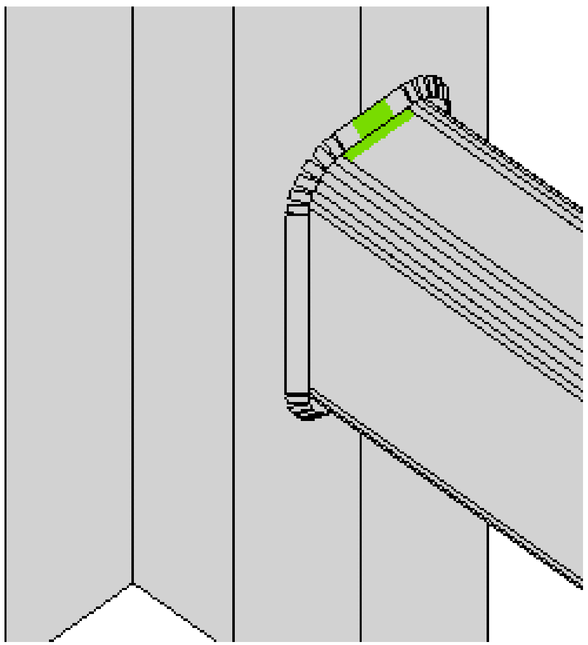
φ = 2,0 mrad

S_j = 10,6 MNm/rad

Global and local behaviour

Initial plastification in the weld





M = 25 kNm

φ = 2,5 mrad

S_j = 10,0 MNm/rad

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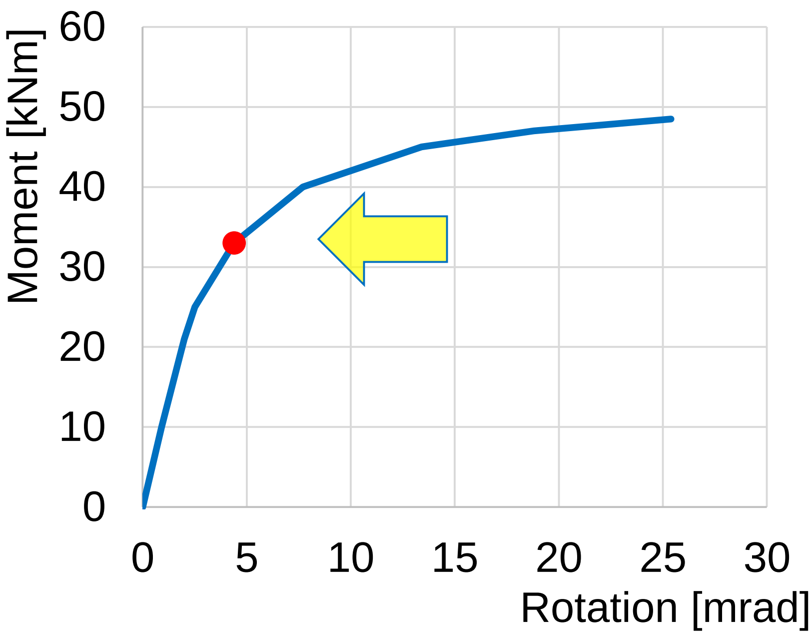
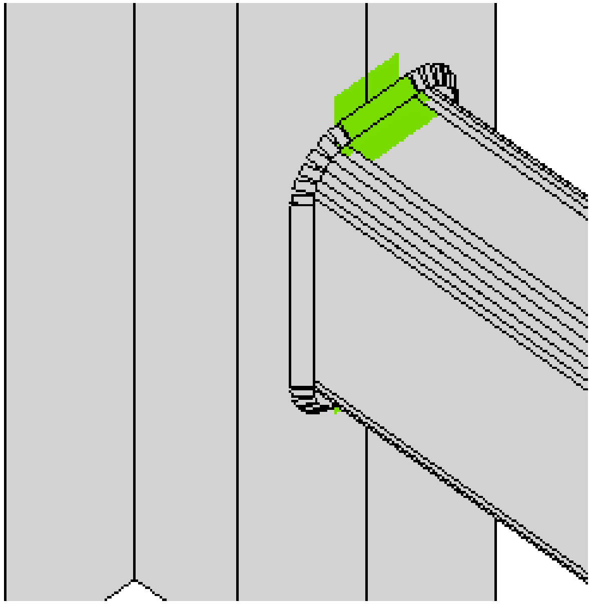
Global and local behaviour

Initial plastification in the open section flange





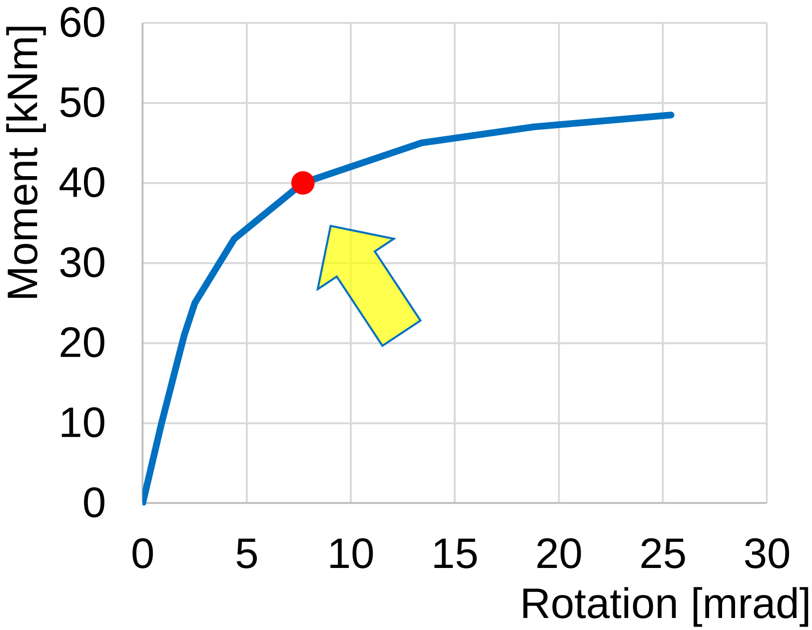
M = 33 kNm

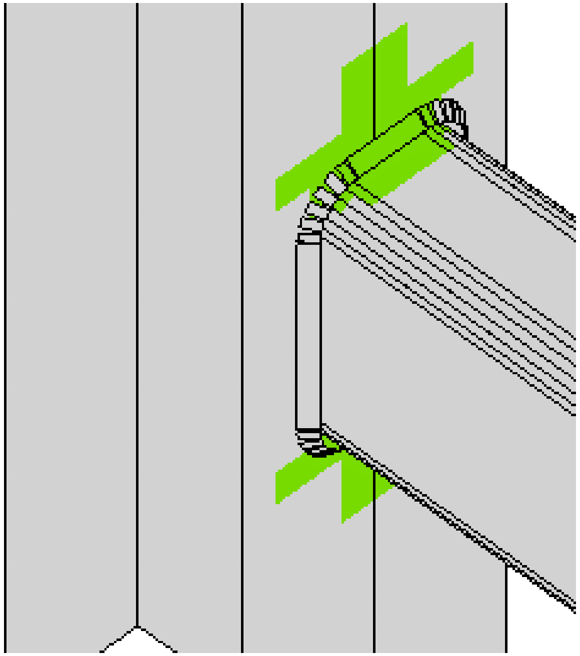
φ = 4,4 mrad

S_j = 7,6 MNm/rad

Global and local behaviour

Initial plastification in the RHS brace roundings





M = 40 kNm

φ = 7,7 mrad

S_j = 5,3 MNm/rad

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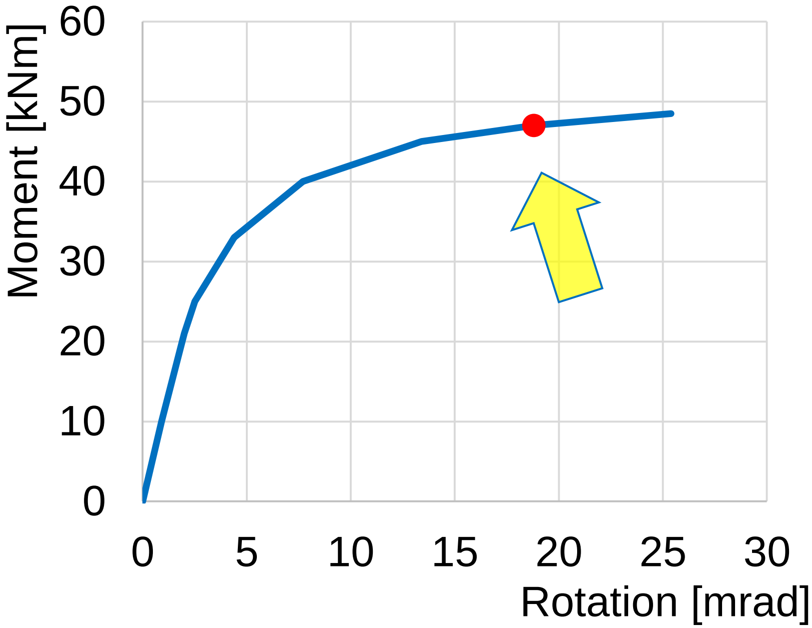
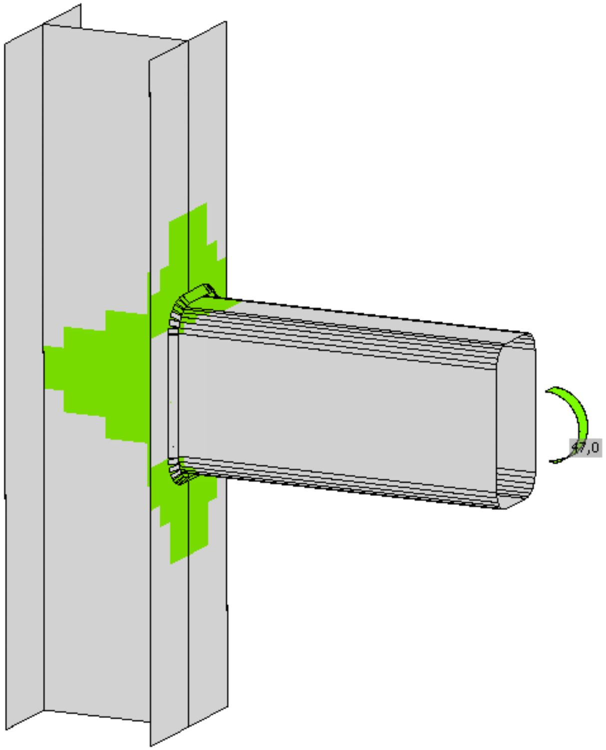
Global and local behaviour

Full plastification through the open section web





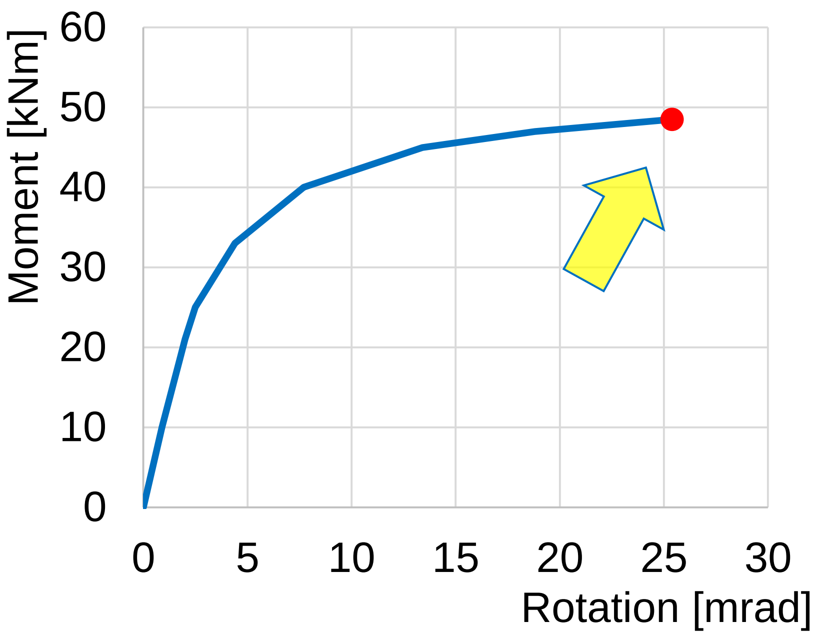
M = 47 kNm

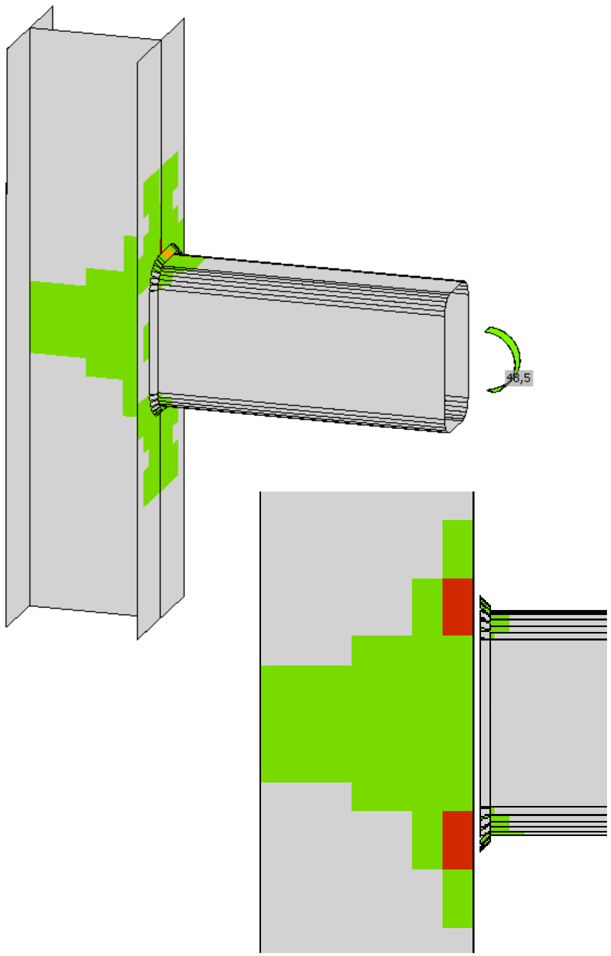
φ = 18,8 mrad

S_j = 2,6 MNm/rad

Global and local behaviour

The open section web reaches plastic strain 5%





M = 48,5 kNm

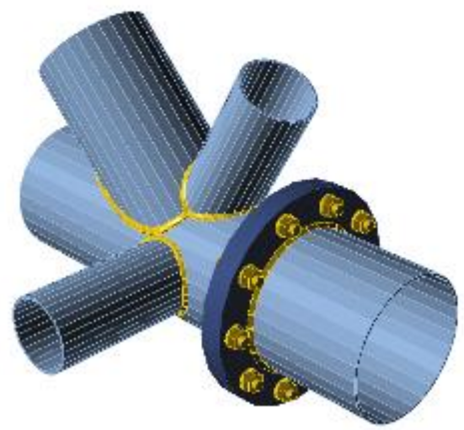
φ = 25,4 mrad

S_j = 2,2 MNm/rad

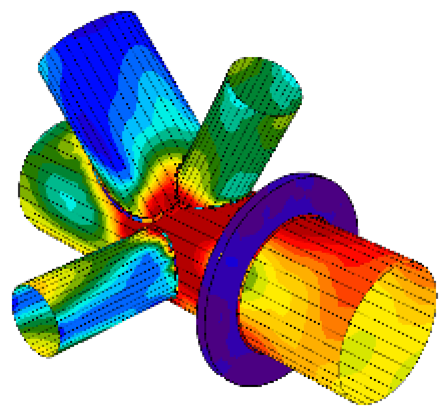
What is the major reason

of using CBFEM for Hollow section joints?

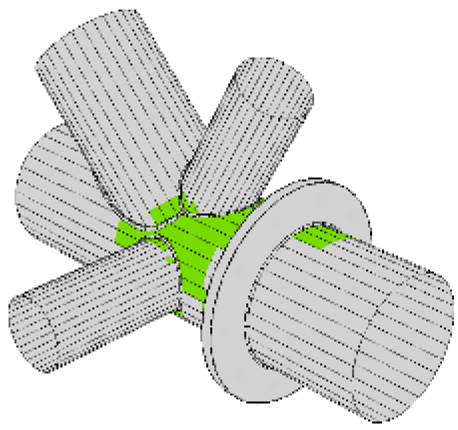
- **The design resistance of generally loaded complex hollow section joints** may be by failure mode method only estimated.
- The example of design procedure by CBFEM is shown below.



3D model



Finite element analyses



Design check

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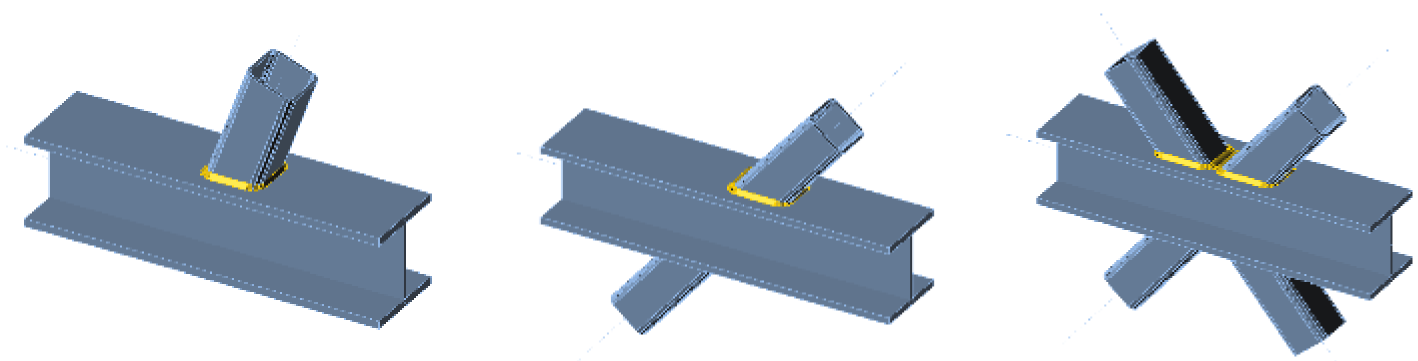
Design tips

- The most economical and common way to connect hollow to open sections is by direct connection without any intersecting plates or gussets, this also gives the most efficient way for protection and maintenance.
- The connections between hollow and open sections can be easily made, since the connecting members are provided with straight end cuts only.



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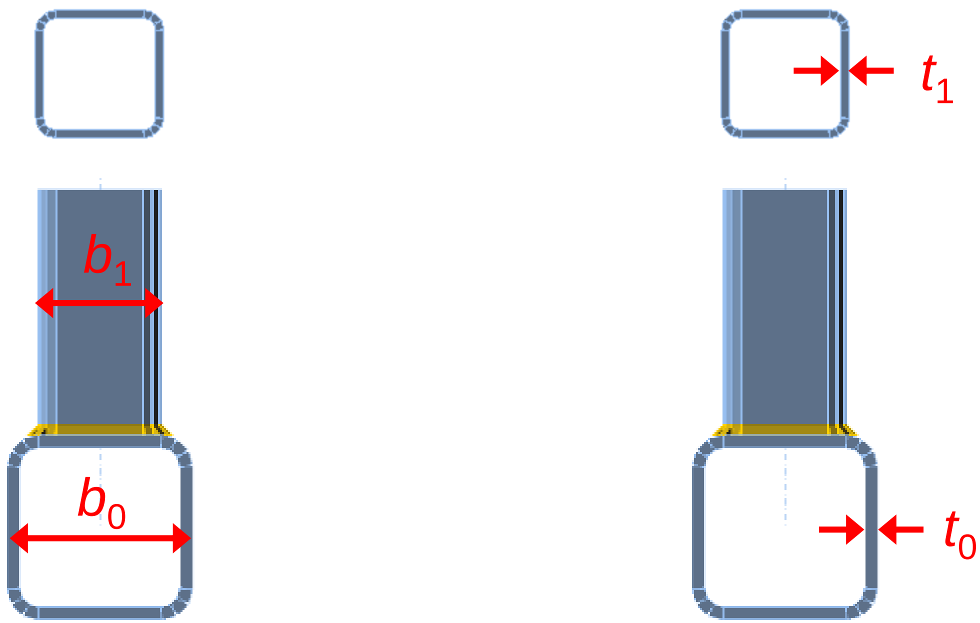
Design tips

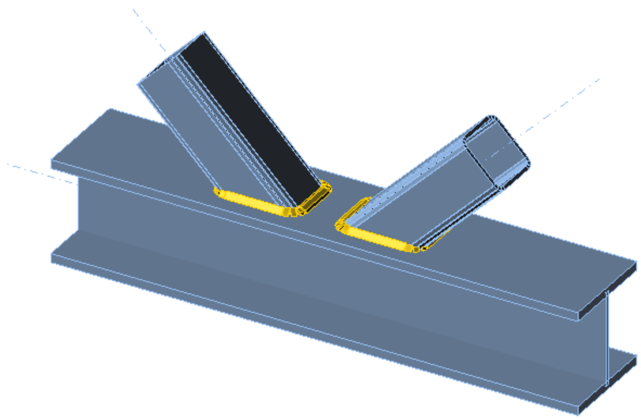
- Tips to optimize design
  - Select relatively stocky chord
  - Select relatively thin brace

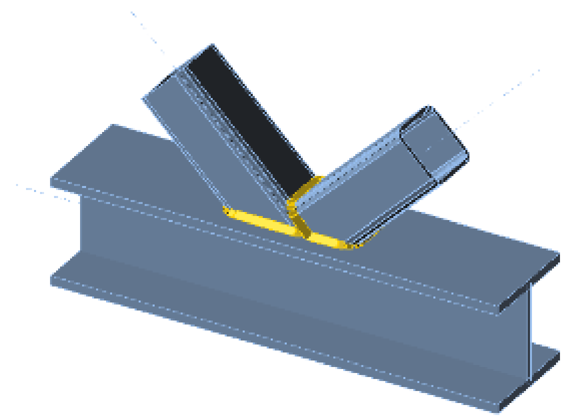


b_1/b_0 as high as possible t_1/t_0 as low as possible

Design tips

- Tips to optimize joint design
  - Consider virtues of gapped K-connections





- Gapped joints are easier and cheaper to fabricate.
- Overlapped joints have higher static and fatigue strength and produce stiffer truss (reduced truss deflections).

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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

- Subject Design of hollow section joints of steel structures.
- Lecture duration 60 mins.
- Keywords Civil Engineering, Structural design, Steel structure, Trusses, Truss girder, Joint, Hollow section joint, Hollow to open section joint, Component Method, Component based Finite Element Method, Eurocode.
- Aspects to be discussed Curve fitting models of joints, Failure mode models of joints, FE models of joints, Failure modes, Component method principle, Application of analytical modelling
- 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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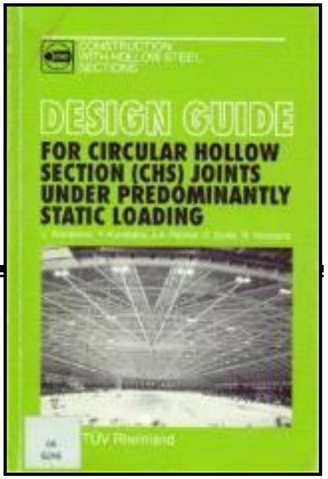
Sources



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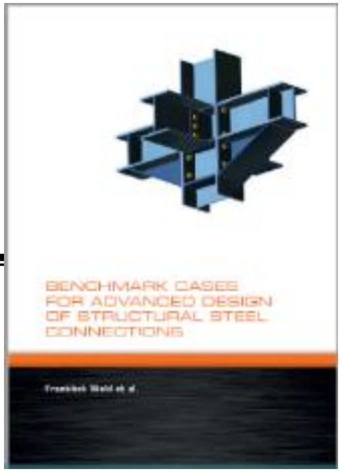
Standards



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