

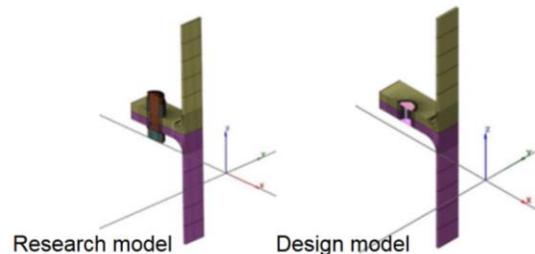
Background of Component Based Finite Element Method



František Wald
Czech Technical University in Prague

Motivation

- Summarise current design of structural connections
- Focus to FEM features
- Explain importance of Validation & Verification



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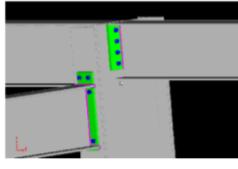
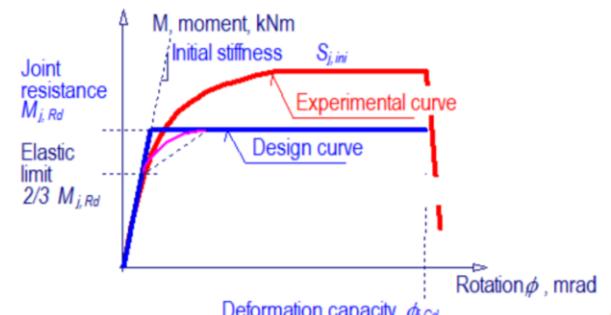
List of contents

- Connection design
 - Models
 - FE analyse
- Validation & verification
- Components modelling
 - Slender plates
 - Bolts
- Connection behaviour
 - Open sections
 - Hollow sections
- Summary

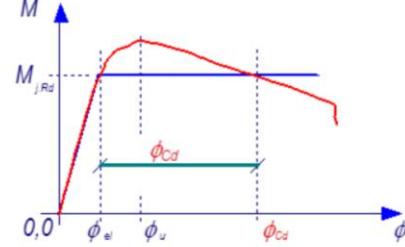


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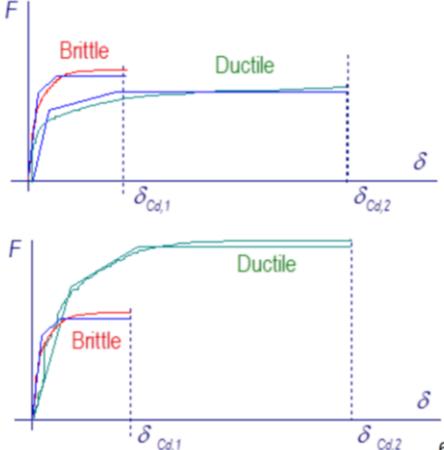
Description of behaviour for design by moment-rotation characteristic

<ul style="list-style-type: none"> ▶ Introduction Connection design <ul style="list-style-type: none"> Models Hollow sections Component method FE analyse Validation and verification Componentbased FEM <ul style="list-style-type: none"> Slender plates Bolted joints Connection behaviour <ul style="list-style-type: none"> Open sections Hollow sections Summary 	<p>Connection exposed to bending</p> <ul style="list-style-type: none"> • Rotational stiffness • Moment resistance • Rotation capacity  <div style="text-align: center; margin-top: 20px;">  </div>
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Deformation/rotation capacity

<ul style="list-style-type: none"> ▶ Introduction Connection design <ul style="list-style-type: none"> Models Hollow sections Component method FE analyse Validation and verification Componentbased FEM <ul style="list-style-type: none"> Slender plates Bolted joints Connection behaviour <ul style="list-style-type: none"> Open sections Hollow sections Summary 	<ul style="list-style-type: none"> • For safety <ul style="list-style-type: none"> – Seismic design – Plastic global analyses • Ductile components <ul style="list-style-type: none"> – Plate in bending – Column web in shear • Brittle components <ul style="list-style-type: none"> – Bolts, welds 
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**Rotation capacity
Upper material properties**

<ul style="list-style-type: none"> ▶ Introduction Connection design <ul style="list-style-type: none"> Models Hollow sections Component method FE analyse Validation and verification Componentbased FEM <ul style="list-style-type: none"> Slender plates Bolted joints Connection behaviour <ul style="list-style-type: none"> Open sections Hollow sections Summary 	<ul style="list-style-type: none"> ○ Question of the <u>Actual yield strength</u> 
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Joint design
European standards

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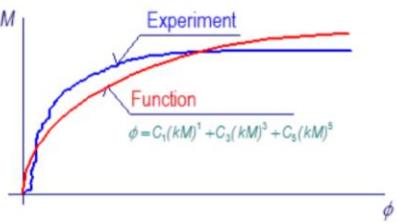
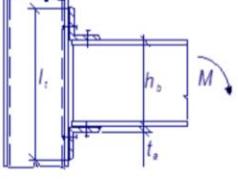


Design approaches for structural joints

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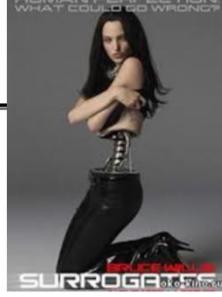
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Curve fitting model

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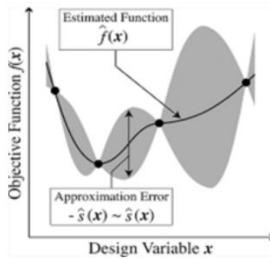
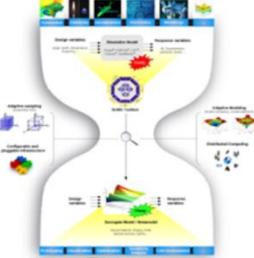
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Surrogate models



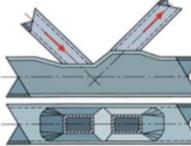
(Meta models)

- Numerical experiments
- Standardised mathematical procedure

SUMO Delf University 10

Hollow section joints

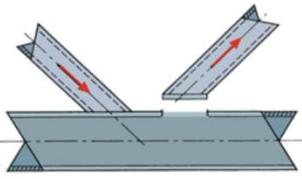
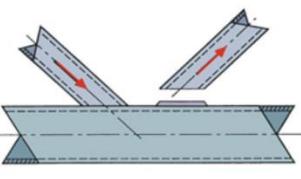


- Design by mixture of
 - Curve fitting
 - Analytical models
- Failure modes
 - CHS, RHS
 - Open and hollow

Mode A:
Plastic failure of the chord face

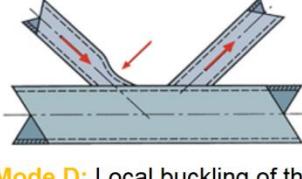
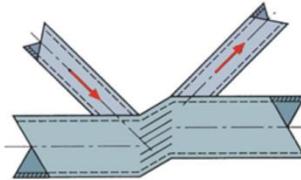



Hollow section joints

Mode B: Punching shear failure of the chord face

Mode C: Tension failure of the web member

Mode D: Local buckling of the web member

Mode E: Overall shear failure of the chord

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Hollow section joints

Mode F: Local buckling of the chord walls

Mode G: Local buckling of the chord face

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CIDECT materials

- Background CIDECT materials
 - ISO/FDIS 14346
 - EN 1993-1-8 Chapter 7
- Uni-planar and multi-planar joints
 - Circular, square or rectangular hollow sections
- + Uni-planar joints
 - Combinations of hollow sections with open sections
- Detailed application rules to determine the static resistances of joints in lattice structures

ISO/FDIS 14346: *Static Design Procedure for Welded Hollow Section Joints – Recommendations*, ISO, IIW XV-1439-13, 2012.

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Geometrical types of basic joints

- Class 1 and 2 cross sections
- Limits in geometry

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Geometrical types of complex joints

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Failure modes – chord, shear

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	Rectangular	Circular	Chords of I or H										
Chord shear failure													
Punching shear			---										

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Failure modes – brace

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	Rectangular	Circular	Chords of I or H										
Brace failure													
Local buckling													

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**Component based aproach
for hollow section design**

- CIDECA project
- 7 failure modes = 7 components
- Defidend lever arm
- The same equations x enginering frendly aproach
- k_{fa} factors transferred to b_{eff} effective widths

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**Component model
Procedure**

- § Decomposition of joint
- § Component description
- § Joint assembly
- § Classification
- § Representation
- § Modelling in analyses

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**Component model
Prediction accuracy**

- Good accuracy
- M-N Interaction
 - Tests in Prague

The top graph plots Normal force (kN) against Moment (kNm). It shows Test SN 1500 (red triangles), SN 1000 (blue squares), and Component method (red line). The bottom graph plots Moment (kNm) against Rotation (rad), showing Test SN 1500 (red circles), Prediction by component method (blue line), and Prediction of resistance by interaction (green line).

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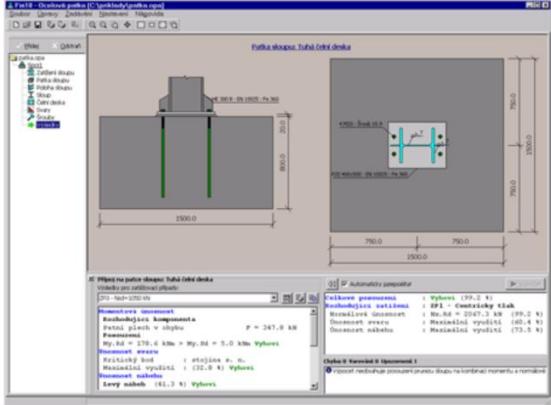
Summary

Component Model Application

- § Design tables
 - § Green book
 - § Blue book
- § Computer programs
- § Simplified hand calculation

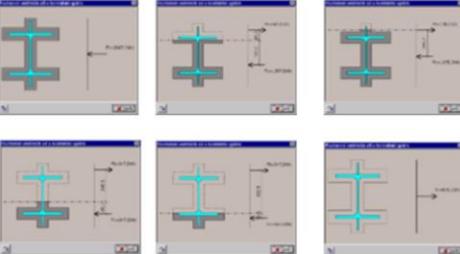
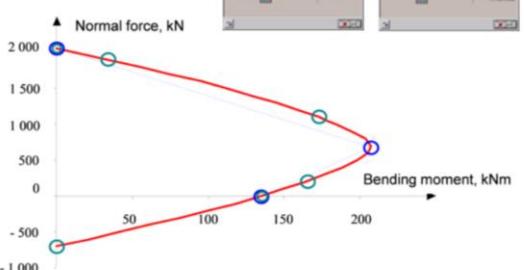
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**Component Model
Design tools**

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**Component Model
Design tools**

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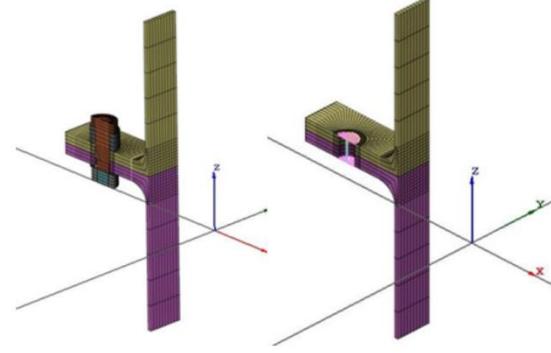
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**Component model
Background references**

Introduction Connection design Models Hollow sections Component method FE analyse Validation and verification Componentbased FEM Slender plates Bolted joints Connection behaviour Open sections Hollow sections Summary 	<ul style="list-style-type: none"> • Zoetemeijer P.: Summary of the research on bolted beam-to-column connections, TU-Delft report 26-6-90-2, 1990. • Zoetemeijer P.: Summary of the Research on Bolted Beam-to-Column Connections (period 1978 - 1983), Ref. No. 6-85-M, Steven Laboratory, Delft, 1983. • Zoetemeijer P.: Proposal for Standardisation of Extended End Plate Connection based on Test results - Test and Analysis, Ref. No. 6-83-23, Steven Laboratory, Delft, 1983. • Jaspert J.P., Design of structural joints in building frames, Prog. Struct. Engng Mater., 4, 2002, 18–34. • Wald F., Sokol Z., Steenhuis M. and Jaspert, J.P., Component Method for Steel Column Bases, Heron 53, 2008, 3-20. • Da Silva Simoes L., Towards a consistent design approach for steel joints under generalized loading, JCSR, 64, 2008, 059-1075. • Beg D., Zupančič E., Vayas I., On the rotation capacity of moment connections, JCSR, 60, 3–5, 2004, 601–620.
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Finite Element models of joint

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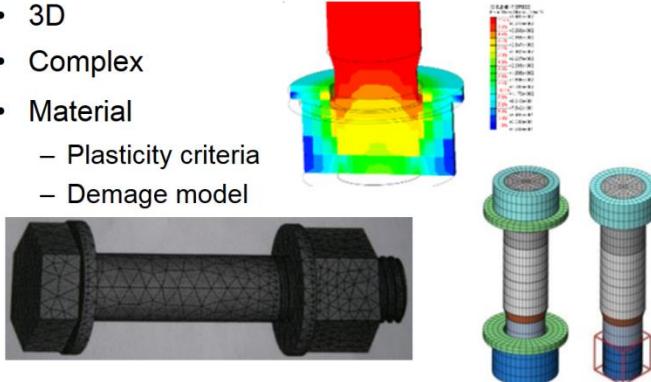


Research model Design model

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Bolt FEM research models

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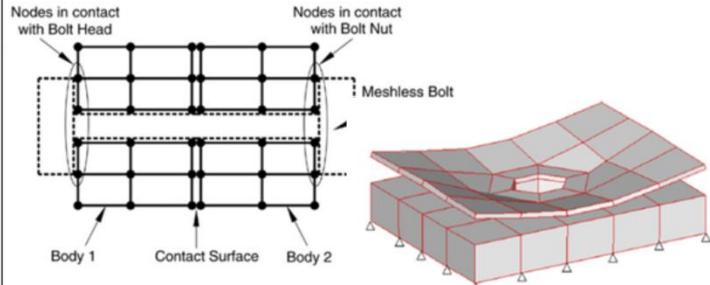


Wu, Z., Zhang, S. and Jiang, S.:
Simulation of tensile bolts in finite element modeling of semi-rigid beam-to-column connections,
International Journal of Steel Structures, 2012, 12/3, 339-350.

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Bolts FEM design models

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Razavia H., Abolmaalia A., Ghassemiehd M., Invisible elastic bolt model concept for finite element analysis of bolted connections, JCSR, 63, 2007, 47-657.

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FEM modelling of bolts

Bolts

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○ Fan model

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Bearing FEM modelling

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Přepnul jste do režimu celé obrazovky. Ukončit režim celé obrazovky

- von-Mises yield criterion
- Demage models

Može P., Beg D., A complete study of bearing stress in single bolt

Connections

FE research models

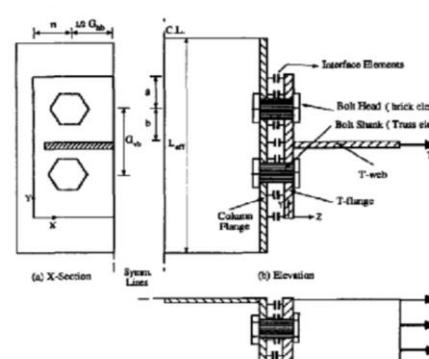
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• N. Krishnamurthy (1978)

- 3 models
- 2D model

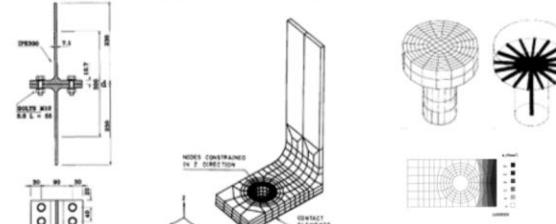
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Connections
FE research models

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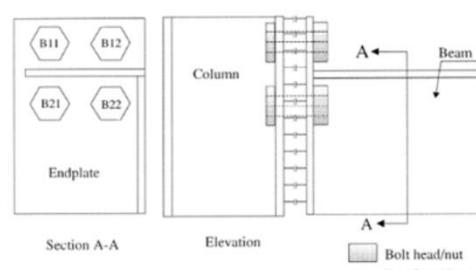
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Connections
FE research models

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Connections
FE research models

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Connections
FE research models

- N.K. Hassan (2004)
- 2D finite element modeling

Applied Moment (m.t.)	Without Stiffeners (mm)	Vertical Stiffener (mm)	V-L & H-R Stiffeners (mm)	Three Bolt Rows (mm)
0	~12	~12	~12	~12
3	~22	~18	~16	~15
6	~32	~22	~18	~16
8	~38	~25	~22	~18

Effect of Stiffener Position on the End-Plate Thickness for a Beam section IPE 300

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Connections
FE research models

- Emmett A. Summer (2003)
- 12 tests, cycling load
- 3D finite element modelling
- Models of finger shims

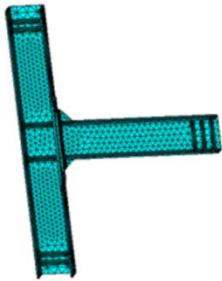
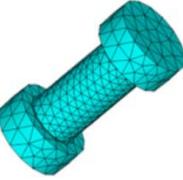
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Connections
FE research models

- Maggi, Ribeiro (2004)
- 12 tests
four bolts extended unstiffened end-plate moment connections tests
- ANSYS 3D models

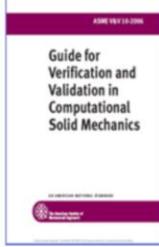
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Connections
FE research models

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Validation and verification procedures

Introduction Connection design Models Hollow sections Component method ➤ FE analyse Validation and verification Componentbased FEM Slender plates Bolted joints Connection behaviour Open sections Hollow sections Summary 	<ul style="list-style-type: none"> • Well developed in FEM theory • To check the physical accuracy • To check the proper use • To check the asked design level <div style="text-align: center; margin-top: 10px;">     </div>
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Definitions of Verification & Validation

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The diagram illustrates the process of Verification & Validation. It starts with 'REALITY' at the top, which feeds into a 'CONCEPTUAL MODEL'. This model then leads to a 'COMPUTERIZED MODEL'. From the computerized model, two paths emerge: one leading to 'Model validation' (highlighted in green) and another leading to 'Model verification' (highlighted in yellow and enclosed in a red box). A vertical dashed line labeled 'Computer simulation' connects the conceptual model to the computerized model. Arrows indicate the flow: 'Model development' from reality to the conceptual model, 'Analysis' from the conceptual model to the computerized model, and 'Programming' from the computerized model back to the conceptual model.

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

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The diagram illustrates an iterative modeling process. It begins with 'Reality of interest', which undergoes 'Conceptual modeling' to produce a 'Mathematical (Conceptual) Model'. This model is used for 'Validation Experiments'. The results of these experiments lead to 'Model validation' and 'Model update', which then feed back into the 'Mathematical (Conceptual) Model'. Additionally, 'FE model development' also feeds into the mathematical model. Finally, 'Model verification' is performed on the 'Computer (Computational) Models'.

Kwasniewski L. (2009) On practical problems with verification and validation of computational models, Archives of Civil Engineering, LV, 3, 323-346.

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Spectacular example of a software bug

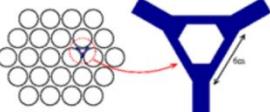
F-22 Squadron Shot Down by the International Date Line (2007)
Maj. Gen. Don Sheppard (ret.):
"...At the international date line, whoops, all systems dumped and when I say all systems, I mean all systems, their navigation, part of their communications, their fuel systems.
.....
It was a computer glitch in the millions of lines of code, somebody made an error in a couple lines of the code and everything goes."

\$120 million F-22 Raptor

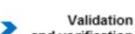
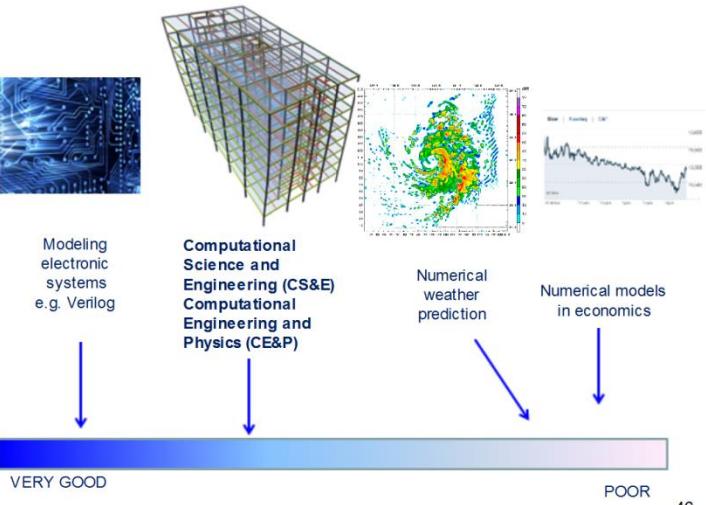
<http://www.defenseindustrydaily.com>

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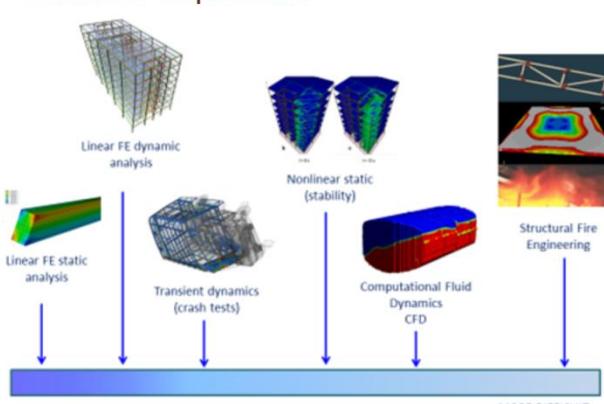
**Famous warning
Sinking offshore platform Sleipner A**

Introduction Connection design Models Hollow sections Component method FE analyse  Validation and verification Componentbased FEM Slender plates Bolted joints Connection behaviour Open sections Hollow sections Summary 	<ul style="list-style-type: none"> Failure in a cell wall Serious crack and leakage Pumps were not able to cope with Combination of a serious error in FEM Insufficient anchorage of the reinforcement in a critical zone 
	<ul style="list-style-type: none"> Inaccurate finite element approximation Linear elastic model of the tricell NASTRAN Shear stresses underestimated by 47 % Certain concrete walls not thick enough 
	<ul style="list-style-type: none"> Total economic loss of about \$700 million <p>http://www.ima.umn.edu/~arnold/disasters/sleipner.html</p>  <p style="text-align: right;">45</p>

What are the predictive capabilities of our computer simulations?

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Computational Science and Engineering (CS&E)

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Hierarchy validation and verification

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System response quantity SRQ

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- Validation is based on the comparison between computational results and experimental data
- An experiment can provide much less information than the calculation
- Selection of the system response quantity (SRQ) is limited by the experiment output

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Validation domains

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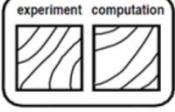
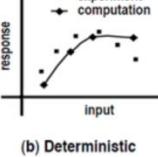
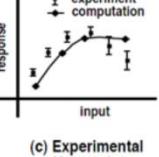
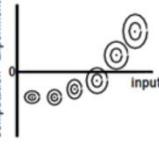
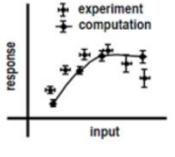
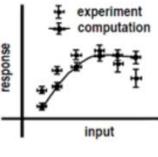
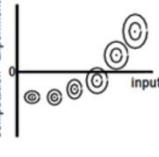
Application domain
defines the intended boundaries for the predictive capability of the computational model

Validation domain
characterizes the representation capabilities of the experiment.

W.L. Oberkampf, T.G. Trucano, C. Hirsch, Verification, validation, and predictive capability in computational engineering and physics, Appl. Mech. Rev. 57 (5), 345–384, 2004

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Validation metrics

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W.L. Oberkampf, T.G. Trucano, C. Hirsch, Verification, validation, and predictive capability in computation engineering and physics, Appl. Mech. Rev. 57 (5), 345–384, 2004.

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Evaluation of Mechanical Structural Response

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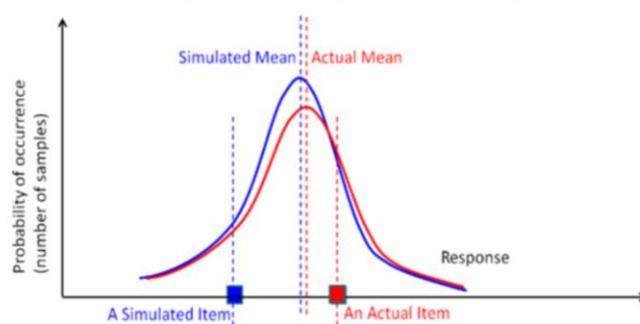
Verification - Mesh density study

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Verification and Validation of Computer Simulations

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FE model well replicates the experiment

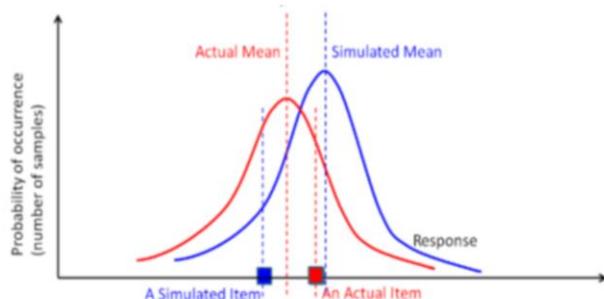


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Effect of calibration



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Databases of benchmark problems

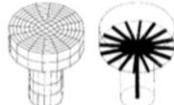
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- **National Agency for Finite Element Methods and Standards (NAFEMS)** www.nafems.org
 - ~ 280 verification benchmarks
- **ABAQUS Benchmarks Manual**
 - 264 (93-NAFEMS, 15-thermal analysis) Verification Manual, Example Problems Manual
- **ANSYS®** - around 250 problems
- **Fire engineering**
 - Standardised ISO/FDIS 16730 Fire safety engineering — Assessment, verification and validation of calculation methods, Geneva, 2008.
 - DIN EN 1991-1-2

56

Validation of research model of T stub

- Modern history
 - **1997**
 - Bursi O. S., Jaspart J. P., Benchmarks for Finite Element Modelling of Bolted Steel Connections, *Journal of Constructional Steel Research*, 43 (1-3), 1997, 17-42.
 - **1999**
 - Virdi K. S. et al, *Numerical Simulation of Semi Rigid Connections by the Finite Element Method*, Report of Working Group 6 Numerical, Simulation COST C1, Brussels Luxembourg, 1999.



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Hierarchy of benchmark studies for structural steel joints

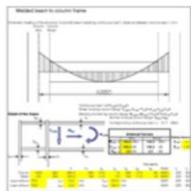
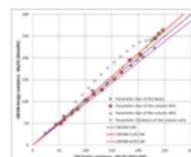
- **Welded joints**
 - In shear
 - In bending
 - Long joint
 - Flexible plate
- **Bolted connections**
 - T-stub in tension
 - Splices in shear
 - Generally loaded end plate
- **Slender plate in compression**
 - Triangular haunch
 - Stiffener of column web
 - Plate in compression between bolts
- **Hollow section joints**
 - CHS, RHS members
 - Hollow and open sections
- **Column bases**
 - T stub in compression and in tension
 - Generally loaded base plate



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Verification and Benchmark cases

Chapters

Description <ul style="list-style-type: none"> ↳ Component method ↳ CBFEM ↳ Force-deformation curve ↳ Global behaviour ↳ Verification of resistance ↳ Global verification Initial stiffness, Resistance, Deformation capacity ↳ Benchmark case 	 
--	--

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Component based FEM

- Joint analyses by FEM
 - Design material model
- Component behaviour
 - Connectors
 - Bolts
 - In tension
 - In shear
 - Welds
 - Anchor bolts
 - Slender plates
 - Concrete block

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Material for FE design model

- Bilinear ideal elastic-plastic model

Absign input	True stress [MPa]	Plastic strain
Test	313	0.047
TEA	423.5	0.18
Design	506.4	0.68

Moze P., Beg D., A complete study of bearing stress in single bolt connections, JCSR, 9 5 (2014) 126–140

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Plate modelling

- 3D – bricks
- 2D elements - shells

- Shells for design
 - 8 degree of freedom elements
 - 4 nodes (degrades to 3)
 - Allowing plastification, membrane effects, bifurcation

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Design model
Slender plate in compression

- Column web
- Stiffeners

The diagram illustrates five different configurations of stiffener connections on a column web under compression.
 a) A single vertical stiffener at the top edge.
 b) A single vertical stiffener with a horizontal flange at the top edge.
 c) Two vertical stiffeners with a horizontal flange at the top edge.
 d) A single vertical stiffener with a horizontal flange at the middle edge.
 e) Two vertical stiffeners with a horizontal flange at the middle edge.

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FE research model
on T triangular stiffener

- Von-Mises stress distribution for beam-to-column joint

In frame at a separate element

The figure displays two FEA results for a T triangular stiffener.
 On the left, a 3D finite element model of a beam-to-column joint is shown with a color-coded stress distribution. A color bar indicates stress values from 12.8 to 303 MPa.
 On the right, a separate element model of the T-stiffener is shown with a color-coded stress distribution. The dimensions are 200 mm by 200 mm, and the thickness is t = 8 mm. A coordinate system shows the top edge under compression (σ_c) and the side edge under shear (τ). A color bar indicates stress values from 12.8 to 303 MPa.

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Research FEM

- Shell elements, true-stress true strain material model, mesh sensitivity
- Geometrical and material nonlinear model with imperfections (GMNIA)
- Imperfections based on 1st buckling mode
- Experiments – literature, own
- Code RFEM

The figure shows three 3D finite element models of a T triangular stiffener, each illustrating a different buckling mode. The models are colored according to their displacement or stress distribution. A small blue cube icon is located in the top right corner of the slide.

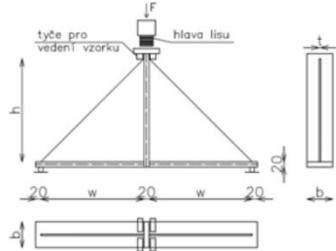
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Experimental research

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- Material tests
- Flanges
 - 3x free edge, 3x partial stiffener, 3x fully stiffening
- Variation of
 - Stiffener thickness t
 - Haunch geometry h and w
 - Flange thickness t_f and width b_f



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Supports and loading

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- Hinges and compression
- Strain gauges LY11-6/120 a XY11-6/120
- Deflectometers
- Loading by steps till collapse



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Stiffener with free edge

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$$h = 400 \text{ mm}, w = 200 \text{ mm}, t = 6 \text{ mm}$$



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Stiffener with free edge

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$h = w = 400 \text{ mm}$, $t = 4 \text{ mm}$ and $t = 6 \text{ mm}$



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Stiffener with partial stiffened edge

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$h = w = 400 \text{ mm}$, $t = 6 \text{ mm}$, $t_f = 6 \text{ mm}$, $b_f = 60 \text{ mm}$



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Stiffener with partial stiffened edge

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$h = w = 400 \text{ mm}$, $t = 6 \text{ mm}$, $t_f = 12 \text{ mm}$, $b_f = 120 \text{ mm}$



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Stiffener with partial stiffened edge

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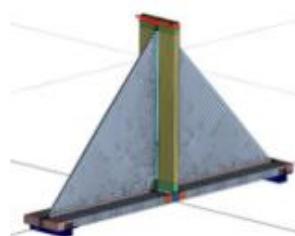
Summary

$h = w = 400 \text{ mm}$, $t = 4 \text{ mm}$, $t_f = 12 \text{ mm}$, $b_f = 120 \text{ mm}$



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- Validation on force-deformation curve $F-\delta$ for resistance
- Vertical deformation at centre
- Vertical deformation at max. amplitude



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Validation of research model Free edge

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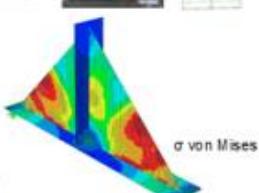
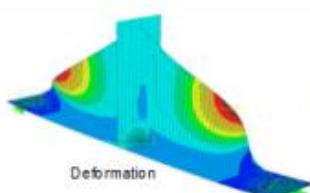
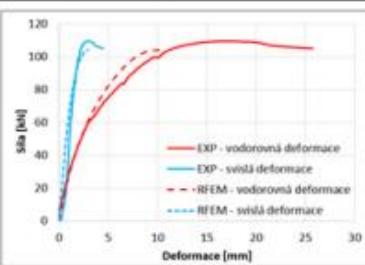
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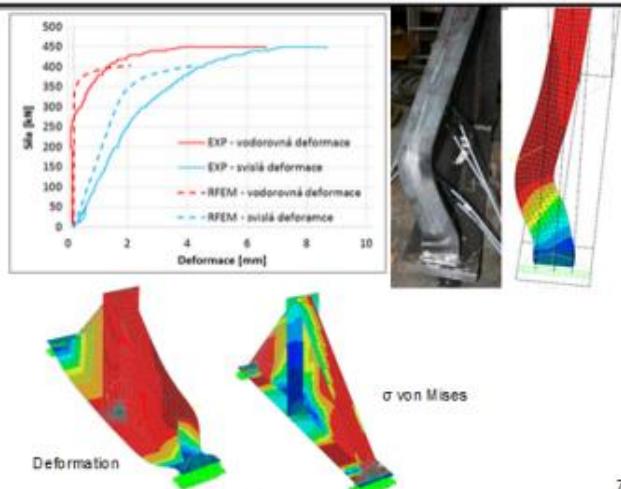
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Validation of research model Partial stiffened edge

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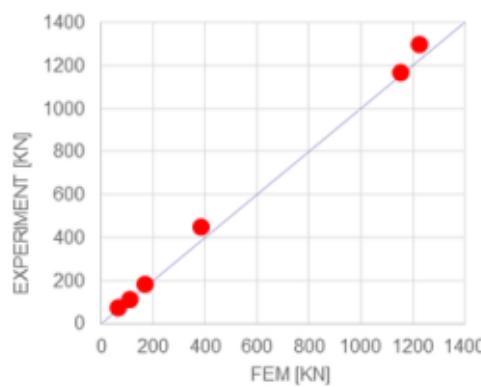


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Validation of FE research model on T triangular stiffener tests

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- Validation of research FEM model for resistance

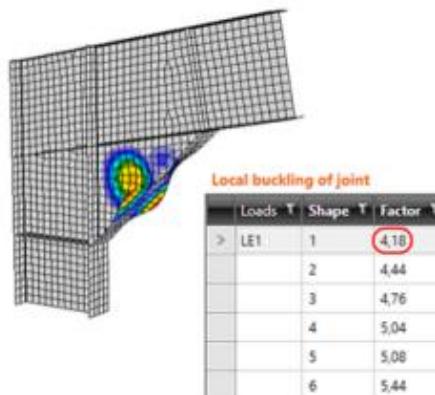


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Design model of slender plate in compression

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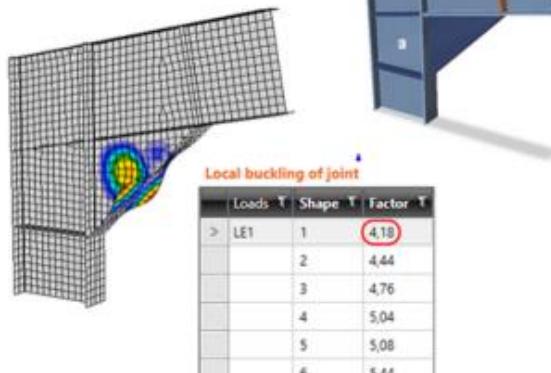
- Buckling analysis



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Design model of slender plate in compression

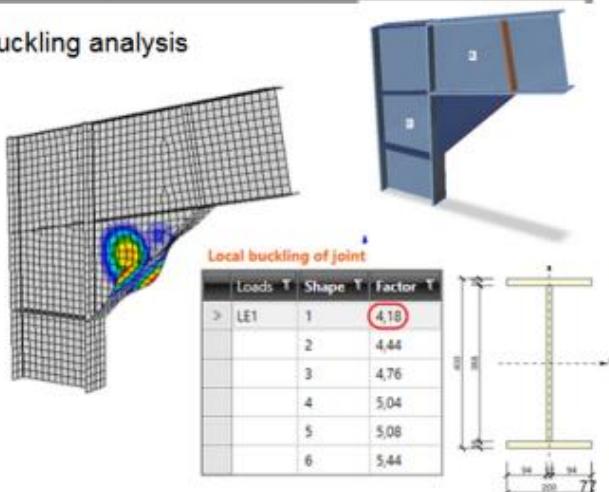
- Buckling analysis



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Design model of slender plate in compression

- Buckling analysis



Design model Slender plate in compression

To eliminate slender plates in joints

Reduced stress method

- According to EN 1993-1-5 Annex B
- Critical buckling factor - Linear buckling analyses α_{cr}
- Load amplifier - Material nonlinear analyses $\alpha_{ult,k}$
- Plate slenderness $\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}$
- Plate buckling reduction factor ρ
- Evaluation $\frac{\rho \cdot \alpha_{ult,k}}{\gamma_{M1}} \geq 1$

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Design model Slender plate in compression

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Connection design

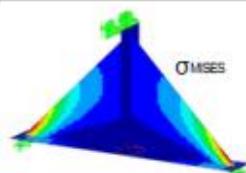
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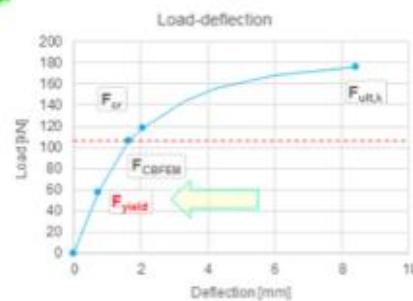


$$\sigma_{Mises} = f_y$$

$$F = 57,6 \text{ kN}$$

$$Z = 0,7 \text{ mm}$$

$$\epsilon = 0,25\%$$



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Design model Slender plate in compression

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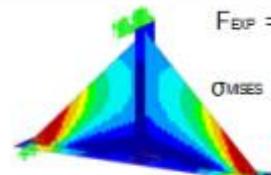
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$$F_{exp} = 109,7 \text{ kN}$$

$$F = 105,8 \text{ kN}$$

$$Z = 1,6 \text{ mm}$$

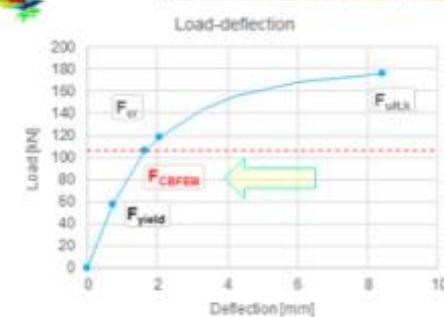
$$\epsilon = 0,7\%$$

$$\alpha_\sigma = 1,123$$

$$\alpha_{ult} = 1,659$$

$$\rho = 0,603$$

$$1,001 > 1 \text{ OK}$$



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Design model Slender plate in compression

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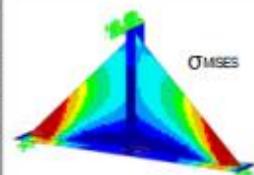
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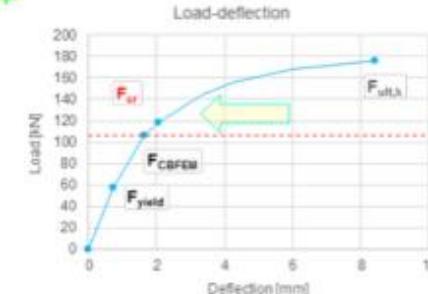


$$F = 118,8 \text{ kN}$$

$$z = 2,1 \text{ mm}$$

$$\epsilon = 1\%$$

$$\alpha_\sigma = 1,0$$



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Design model Slender plate in compression

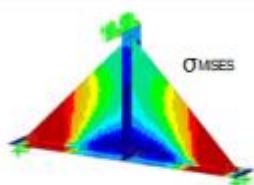
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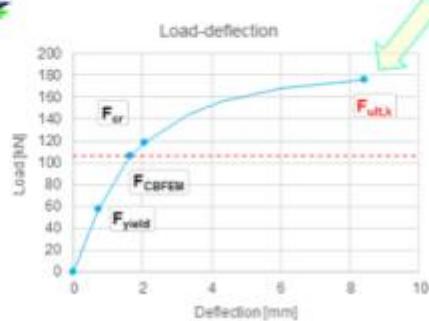
 Summary



$$F = 175,6 \text{ kN}$$

$$z = 8,4 \text{ mm}$$

$$\varepsilon = 5\%$$



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Design model of bolted connections

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- In shear
- In tension
- Nonpreloaded
 - Are preloaded
- Preloaded bolts
 - Controlled slip

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Design model of bolt in tension

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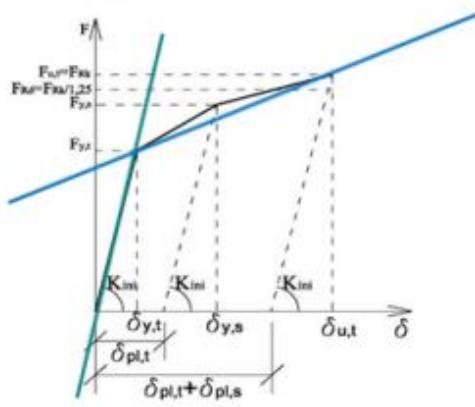
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○ Force-displacement diagram



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Bolted connection

Deformation stiffness of bolt in tension

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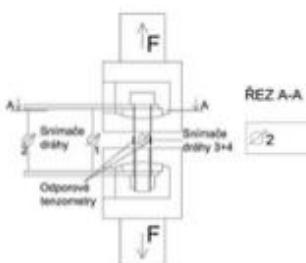
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- o References from literature
- o Experimental research



List of own experiments

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Summary



- o Two failure modes
 - o Rupture of thread
 - o Tearing down of nut

No.	Diameter	Material	Bolt length L	Grip length s	Nut height h	Washer height h_w	Head height h_o
1	M20	8.8	81.5	42.2	15	0	12.6
2	M16	10.9	109	35.4	17	2x4	10.1
3	M16	10.9	108.2	4	17	2x4.1	10.2
4	M16	10.9	108.2	10.5	12.7	2x4.1	10.2
5	M20	8.8	57.7	32.9	15.1	0	12.6
6	M20	8.8	0	99.3	15.6	3.1x3.2	12.6
7	M20	8.8	57.3	34.4	15.5	0	12.5
8	M20	8.8	57.7	32.1	15.2	2x3	12.5
9	M20	8.8	57.7	31.7	15.3	0	12.5
10	M20	8.8	83.4	19.4	30.4	2x2.9	12.7
11	M20	8.8	0	83.5	31	0	12.5
12	M16	10.9	107.7	18.6	17.1	0	10.2
13	M16	10.9	108.1	25.4	12.7	2x4.1	10



Behaviour based on bolt failure

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Connection design
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Hollow sections
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Componentbased FEM
Slender plates
Bolted joints

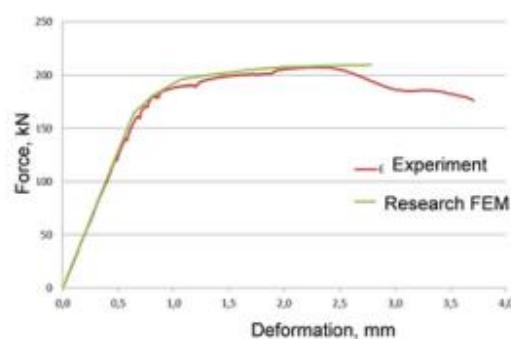
Connection behaviour
Open sections
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Validation for rupture of thread

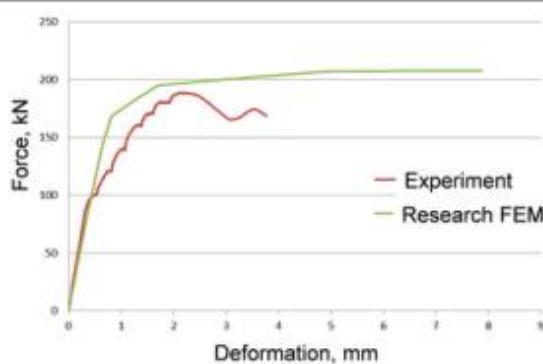
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Validation for tearing down of nut

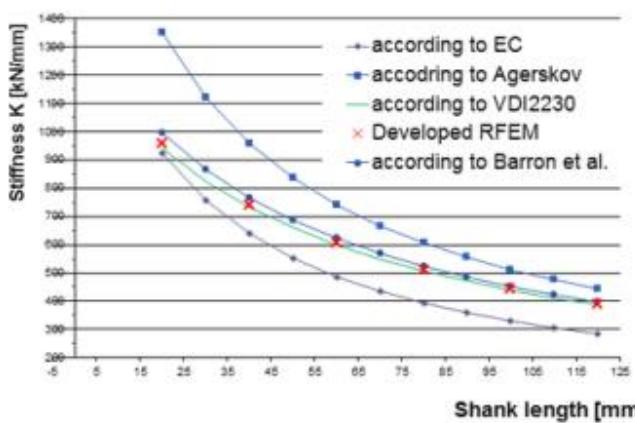
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Parametric study of the bolt tensile stiffness

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Verification of design model of bolt in tension

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Slender plates

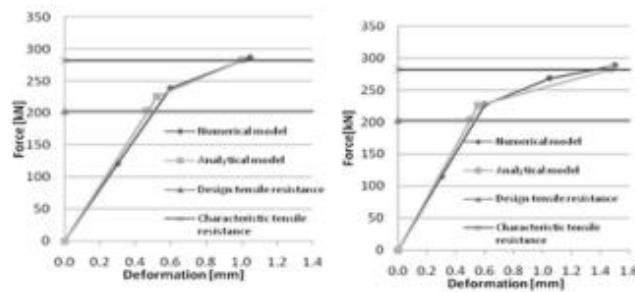
Bolted joints

Connection behaviour

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Thread length 17,6 mm Thread length 28,2 mm

Bolts M24 grade 8.8

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Modelling of T stub behaviour

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Bolts research model

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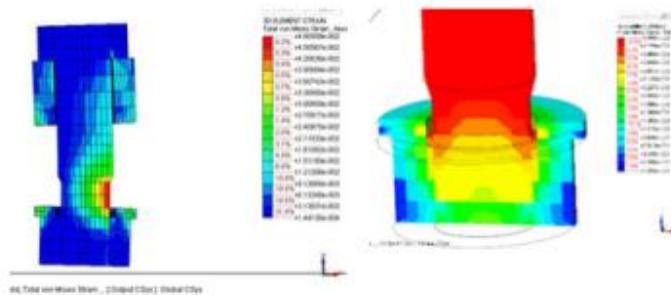
Open sections

Hollow sections

Summary



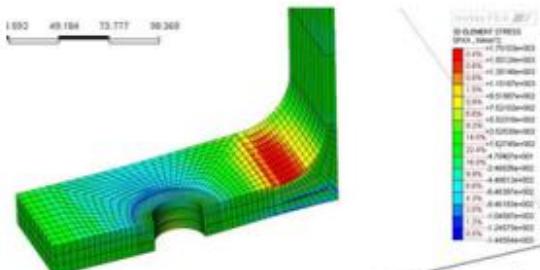
- Unequal stresses distribution
in the threaded part of the bolt



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T stub behaviour Research FE model

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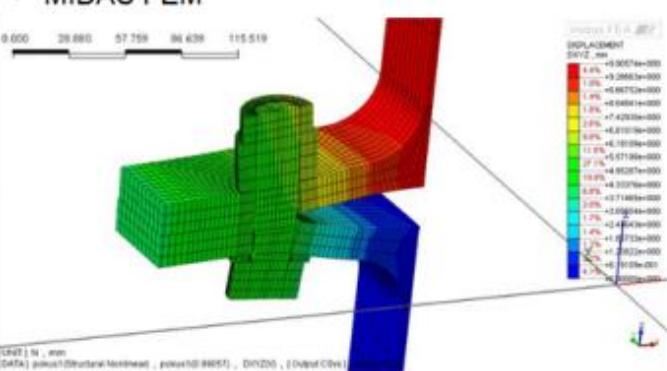


- Mesh sensitivity

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T stub behaviour Research FE model

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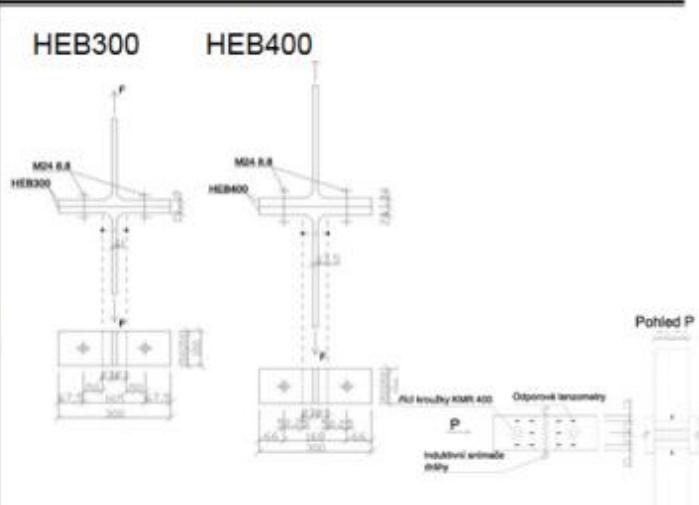


- Bending of bolt
- MIDAS FEM

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Experiment with T stub

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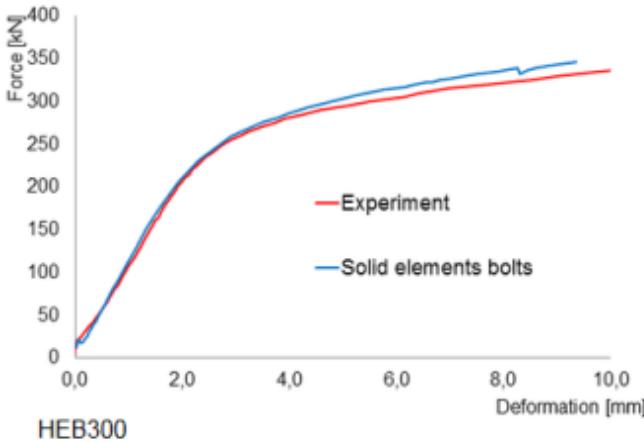
Validation – global deformation

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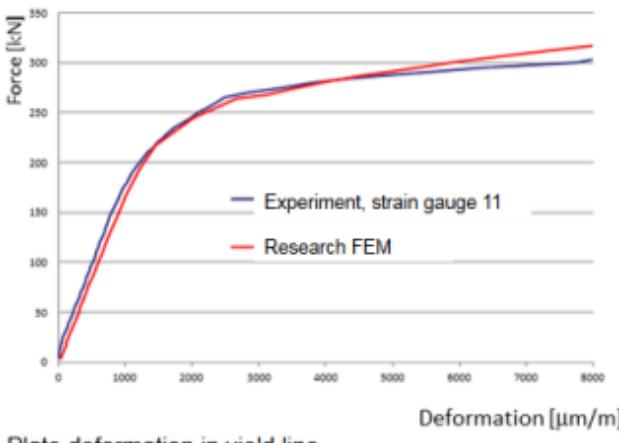
Validation – local deformation

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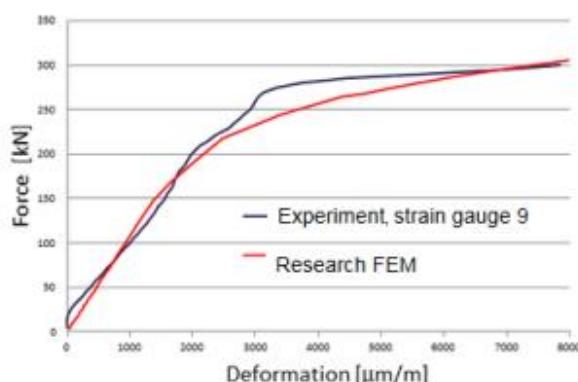
Validation – local deformation

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HEB400



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Validation – global deformation

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Slender plates

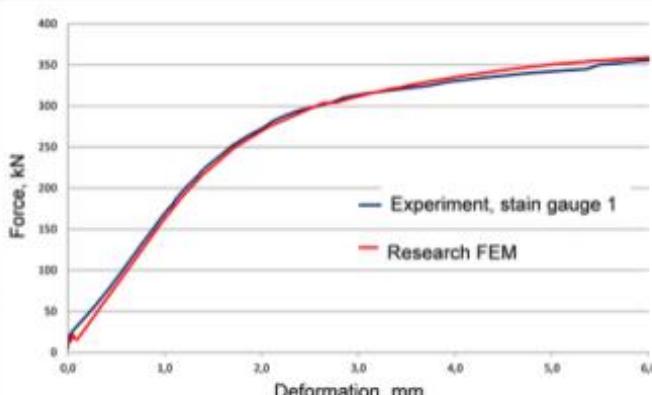
Bolted joints

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HEB 400

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T stub design model Verification

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Slender plates

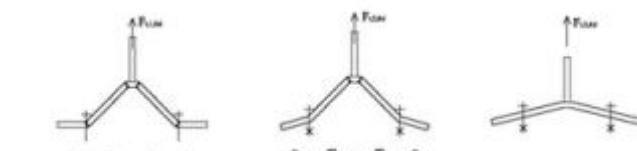
Bolted joints

Connection behaviour

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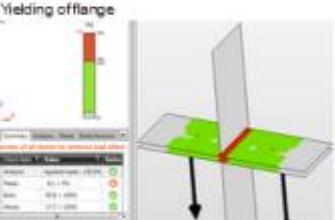
Hollow sections

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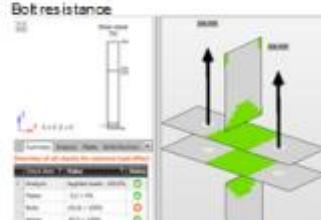


CBFEM:

Yielding offangle



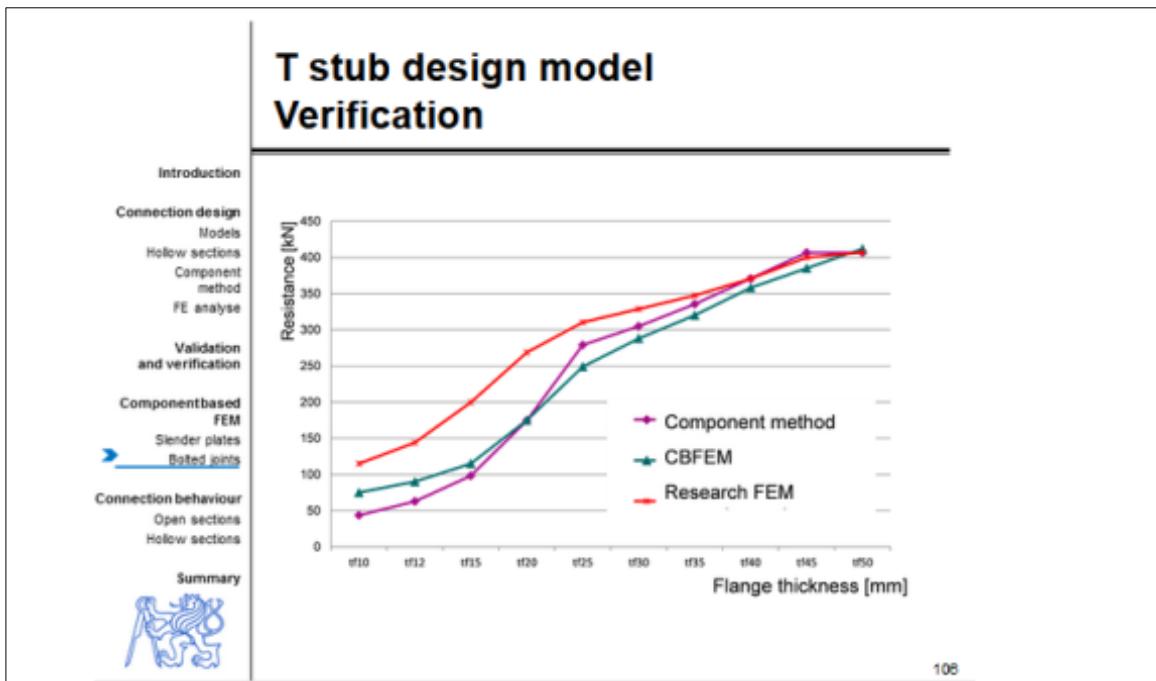
Bolt resistance



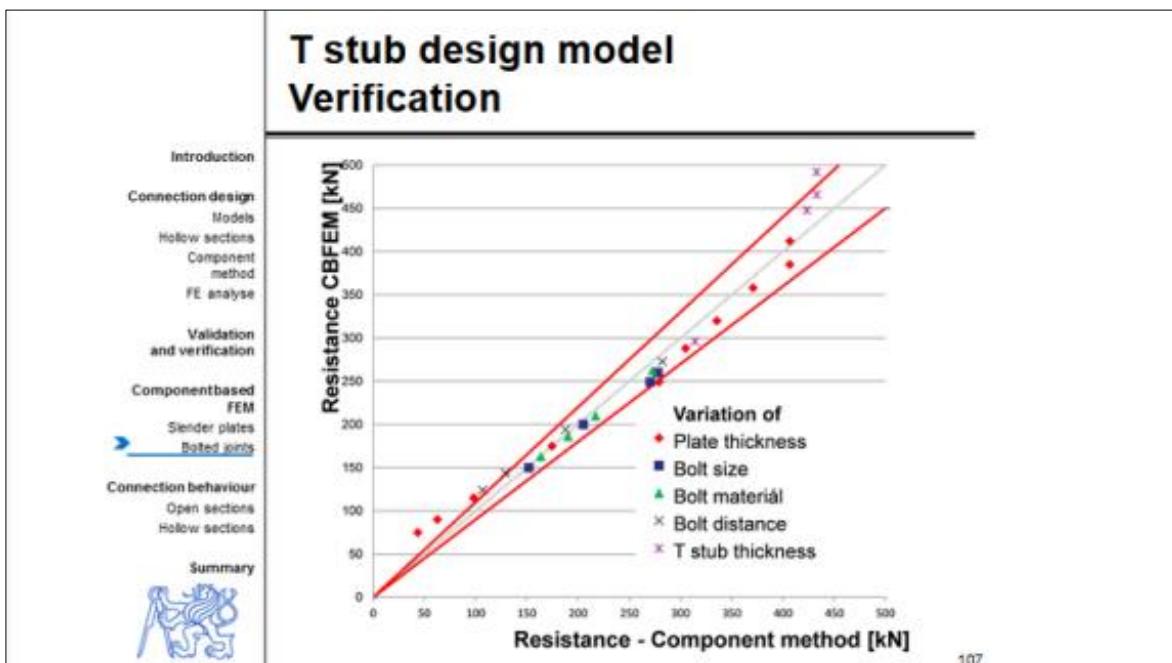
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T stub design model Verification								
Introduction Connection design Models Hollow sections Component method FE analyse Validation and verification Componentbased FEM Slender plates <u>Bolted joints</u> Connection behaviour Open sections Hollow sections Summary		Flange thickness t_f	Component method		CBFEM		3D FEM	
			Resistance [kN]	Failure	Resistance [kN]	Failure	Resistance [kN]	Failure
		10	44	1	75	1	115	1
		12	63	1	90	1	144	1
		15	98	1	115	1	199.7	1
		20	174	1	175	1	268.8	2
		25	279	2	249	1	310.3	2
		30	305	2	288	2	328.7	2
		35	335	2	320	2	347.3	2
		40	371	2	358	2	370.7	2
		45	407	3	385	2	400	2
		50	407	3	412	3	407	3

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Connection behaviour bolted connections of open section

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- Generally
 - Shear
 - Tension
 - Compression
- Research model
 - Validation
- Design model
 - Verification

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Verification bolts in tension and in shear

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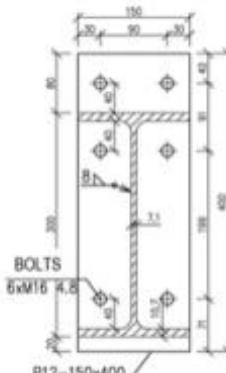
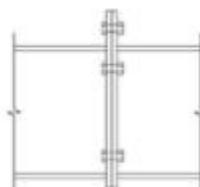
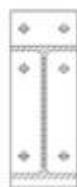
Componentbased FEM
Slender plates
Bolted joints

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Beam splices joint



End plate connection

Steel S355

Plate 12 mm

Bolts M16 4.8

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Verification bolts in tension and in shear

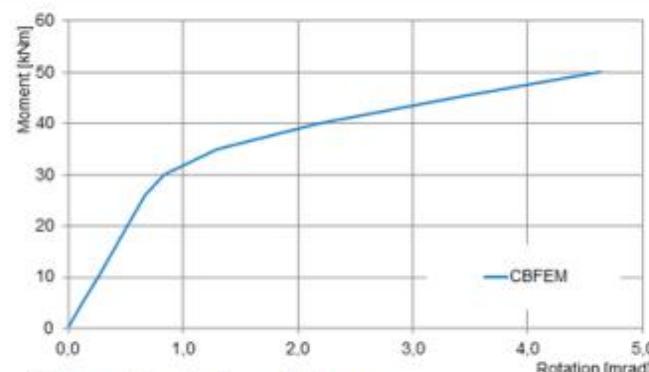
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Moment - rotational diagram
predicted by CBFEM and CM

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Global behaviour bolts in tension and in shear

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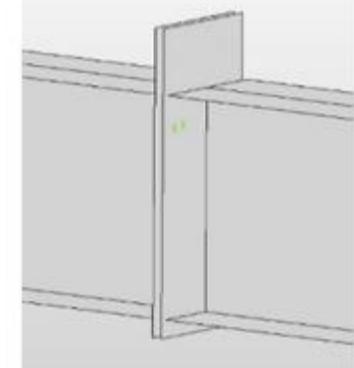
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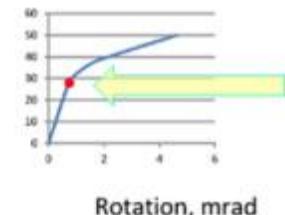
Connection behaviour
Open sections
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Summary



$M=28 \text{ kNm}$
 $\dot{\theta}=0,746 \text{ mrad}$
 $S_i=37,5 \text{ MNm/rad}$

Moment, kNm



Elastic stresses

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Global behaviour bolts in tension and in shear

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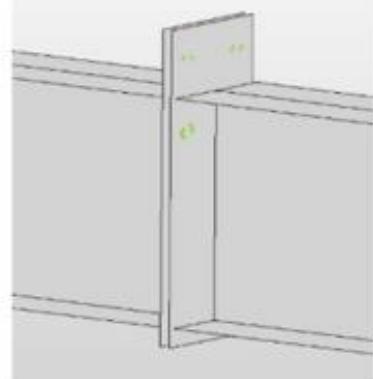
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Componentbased FEM
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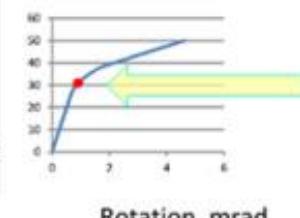
Connection behaviour
Open sections
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Summary



$M=31 \text{ kNm}$
 $\dot{\theta}=0,898 \text{ mrad}$
 $S_i=34,5 \text{ MNm/rad}$

Moment, kNm



Plastification round the lower bolts

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Global behaviour bolts in tension and in shear

Introduction

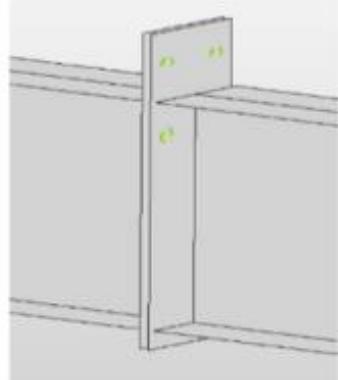
Connection design

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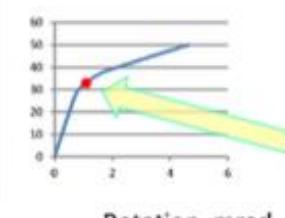
Componentbased FEM
Slender plates
Bolted joints

Connection behaviour
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Hollow sections



$M=33 \text{ kNm}$
 $\dot{\theta}=1,089 \text{ mrad}$
 $S_i=30,3 \text{ MNm/rad}$

Moment, kNm



Rotation, mrad

Plastification round the upper bolts

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Global behaviour bolts in tension and in shear

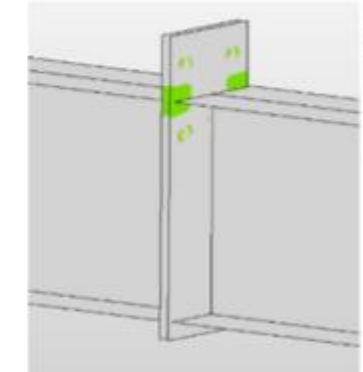
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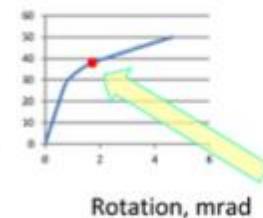
Connection behaviour
→ Open sections
Hollow sections

Summary



$M=38 \text{ kNm}$
 $\dot{\theta}_i=1,714 \text{ mrad}$
 $S_i=22,2 \text{ MNm/rad}$

Moment, kNm



Plastification round the flanges

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Global behaviour bolts in tension and in shear

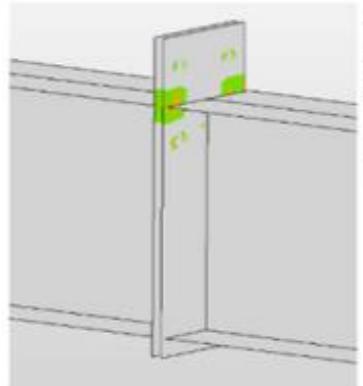
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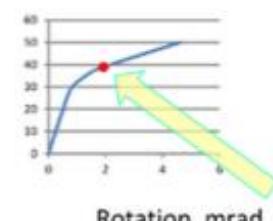
Connection behaviour
→ Open sections
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$M=39 \text{ kNm}$
 $\dot{\theta}_i=1,925 \text{ mrad}$
 $S_i=20,3 \text{ MNm/rad}$

Moment, kNm



Plastification in the web of HEA

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Global behaviour bolts in tension and in shear

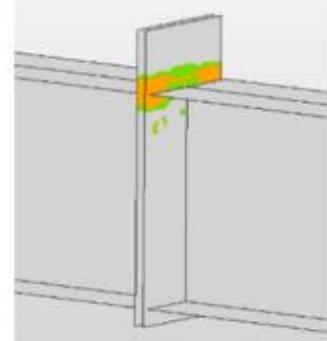
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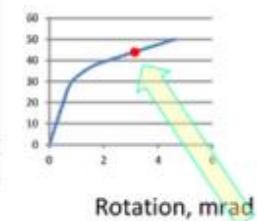
Connection behaviour
→ Open sections
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Summary



$M=44 \text{ kNm}$
 $\dot{\theta}_i=3,138 \text{ mrad}$
 $S_i=14,0 \text{ MNm/rad}$

Moment, kNm



Plastification in the web of HEA

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Global behaviour bolts in tension and in shear

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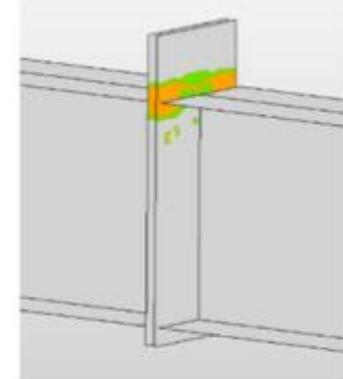
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Componentbased FEM
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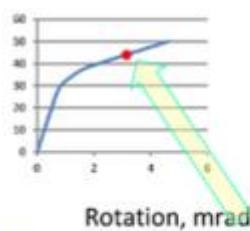
Connection behaviour
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$M=44 \text{ kNm}$
 $\Phi_i=3,138 \text{ mrad}$
 $S_i=14,0 \text{ MNm/rad}$

Moment, kNm



Plastification in the web of HEA

Global behaviour bolts in tension and in shear

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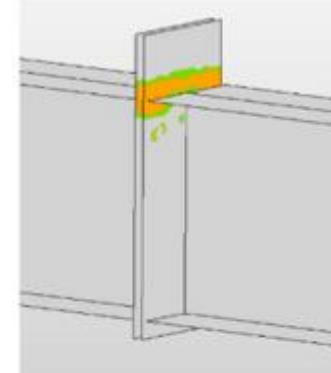
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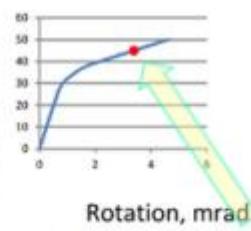
Connection behaviour
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$M=45 \text{ kNm}$
 $\Phi_i=3,383 \text{ mrad}$
 $S_i=13,3 \text{ MNm/rad}$

Moment, kNm



Plastification in the web of HEA

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Global behaviour bolts in tension and in shear

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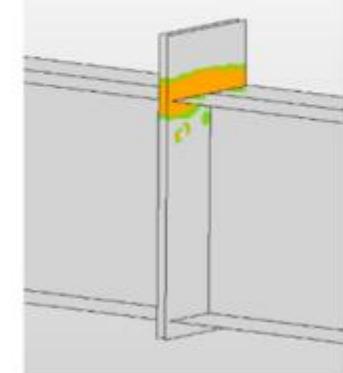
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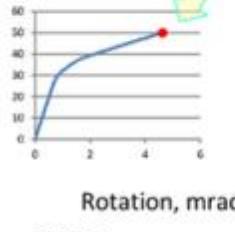
Connection behaviour
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$M=50 \text{ kNm}$
 $\Phi_i=4,626 \text{ mrad}$
 $S_i=10,8 \text{ MNm/rad}$

Moment, kNm



Rotation, mrad

Full plastification in the web of HEA

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Verification bolts in tension

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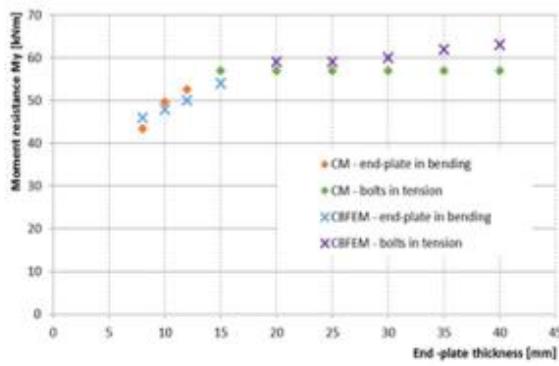
Bolted joints

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End plate thickness

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Verification bolts in tension

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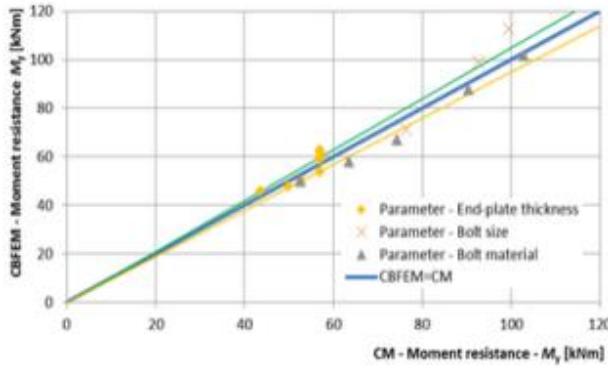
Bolted joints

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Geometrical and material parameter

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Verification bolts in shear

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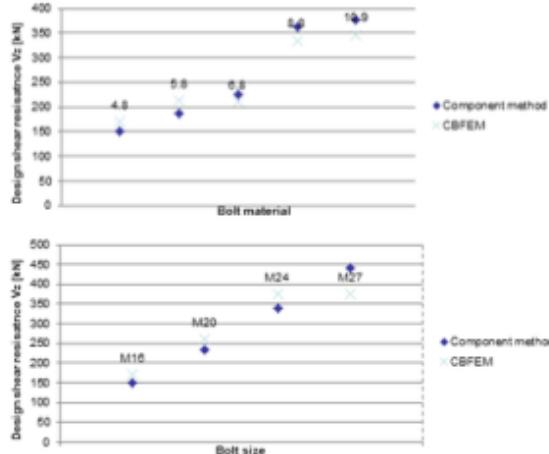
Bolted joints

Connection behaviour

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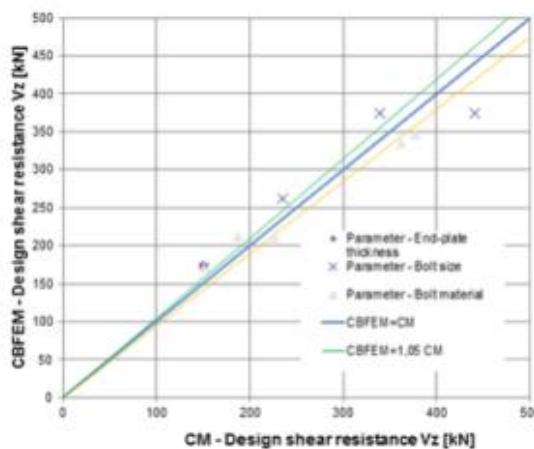
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Verification bolts in shear

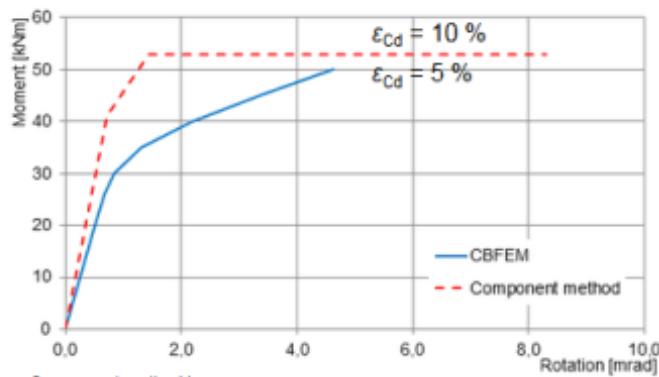
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Verification deformation capacity

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Component method by
 Beg D., Zupančič E., Vayas I., On the rotation capacity of moment connections,
Journal of Constructional Steel Research 60, 3–5, 2004, 601–620

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Prediction of Deformation capacity

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- Material
 - For resistance $\varepsilon_{cd} = 5\%$
 - For deformation capacity $\varepsilon_{cd} = 15\%$

○ Actual yield strength

EN 1998-1-8 cl. 6.2

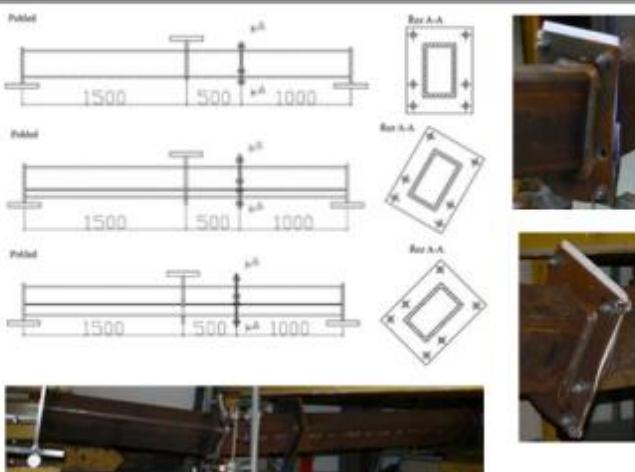
Overstrength factor $g_{ov} = 1,25$

$$f_{y,max} \leq 1,1 g_{ov} f_y$$



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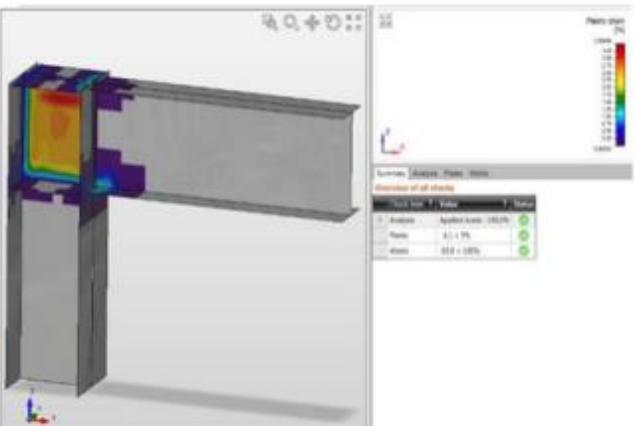
Generally loaded connections
Experiments – beam splices



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Verification to component model
Welded portal frame eaves moment connection



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Beam IPE330 to column HEB260 connection

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Verification to component model
Welded portal frame eaves moment connection

Parameter	Component method		CBFEM-idee RS	
	Resistance [kN/kNm]	Critical component	Resistance [kN/kNm]	Critical component
IPE140	24	Beam flange in compression	27	Beam flange in compression
IPE160	33	Beam flange in compression	34	Beam flange in compression
IPE180	44	beam flange in compression	48	beam flange in compression
IPE200	59	beam flange in compression	67	beam flange in compression
IPE220	77	beam flange in compression	80	beam flange in compression
IPE240	98	beam flange in compression	103	beam flange in compression
IPE270	113	beam flange in compression	125	beam flange in compression
IPE300	142	Web panel in shear	142	Beam flange in compression
IPE330	155	Web panel in shear	154	beam flange in compression
IPE360	168	Web panel in shear	167	Web panel in shear
IPE400	186	Web panel in shear	183	Web panel in shear
IPE450	209	Web panel in shear	202	Web panel in shear
IPE500	231	Web panel in shear	223	Web panel in shear

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Verification to component model Welded portal frame eaves moment connection

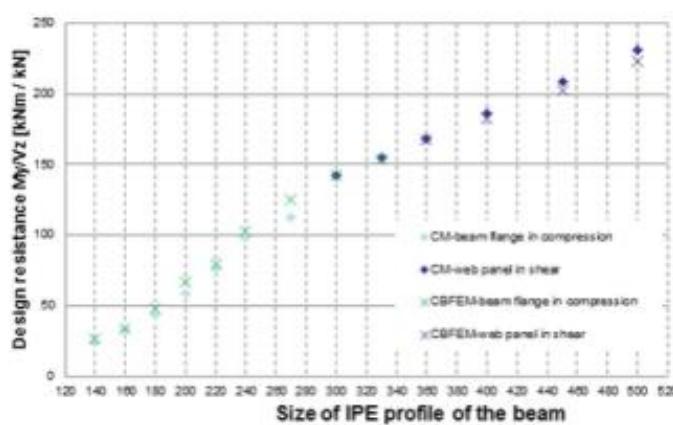
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Verification to component model Welded portal frame eaves moment connection

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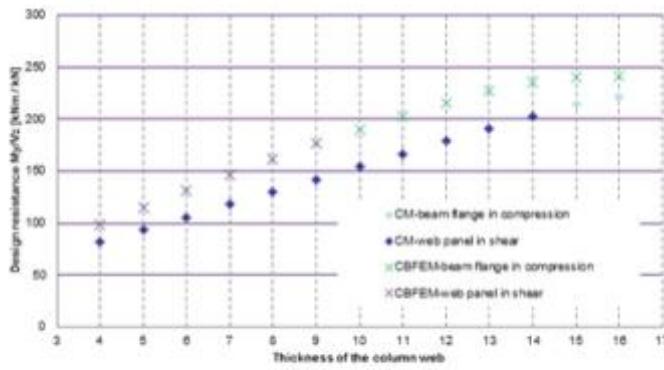
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Thickness of the column web



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Verification to component model Welded portal frame eaves moment connection

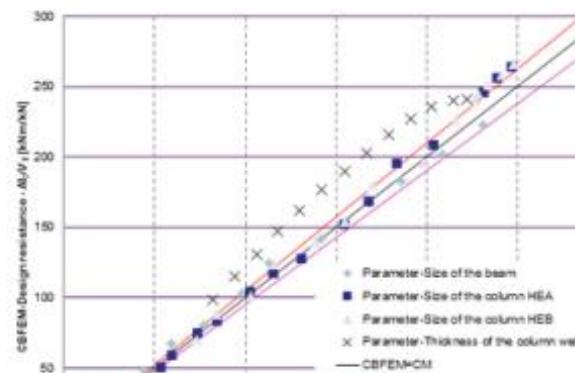
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Joint between open and hollow section

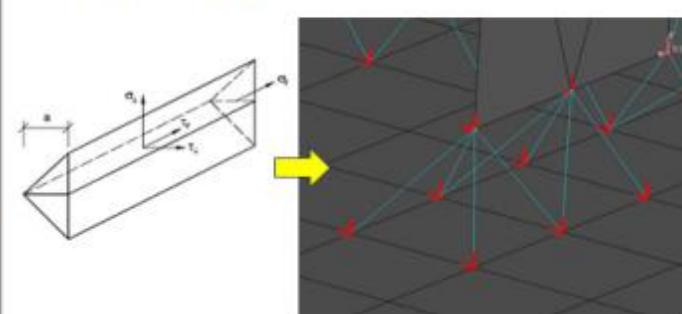
- Verification
 - Welds
 - FEM meshing
- Benchmark case
 - HEA 240 and hollow section RHS 180x100x10
 - Loaded by bending moment and shear force



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Welds for FEM design model

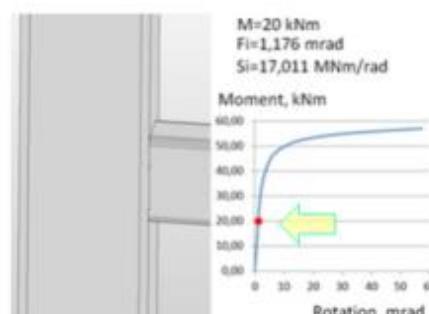
- Model of weld
 - - stiffness, resistance, deformation capacity
 - - stiffness, resistance, deformation capacity
 - - neglected



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Joint between open and hollow section

- Verification
 - Welds
 - FEM meshing
- Benchmark case
 - HEA 240 and hollow section RHS 180x100x10
 - Loaded by bending moment and shear force



M=20 kNm
Fi=1,176 mrad
Si=17,011 MNm/rad

Moment, kNm

Rotation, mrad	Moment, kNm
0	0
10	20
20	40
30	50
40	55
50	58
60	59

Rotation, mrad

Elastic stage

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Joint between open and hollow section

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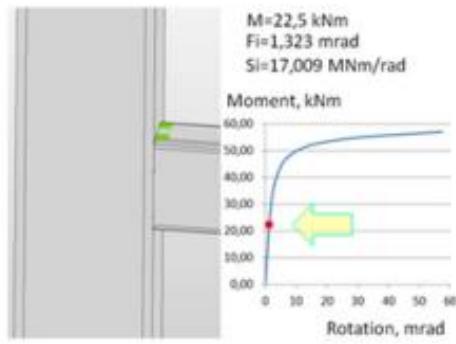
Bolted joints

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Plastification
of the hollow section RHS upper flange

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Joint between open and hollow section

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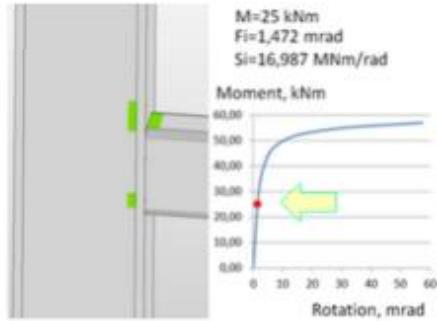
Bolted joints

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Initial plastification
in the open section web

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Joint between open and hollow section

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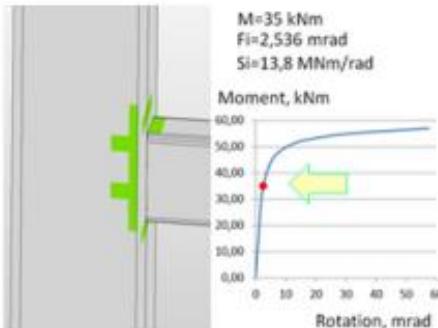
Bolted joints

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Initial plastification
in the open section flange

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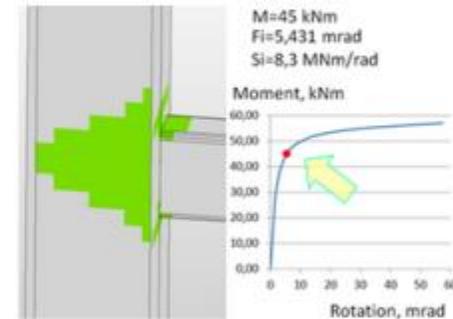
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Full plastification
through the open section web

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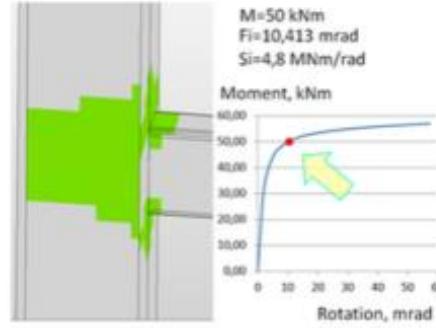
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Initial plastification
in the hollow section RHS web

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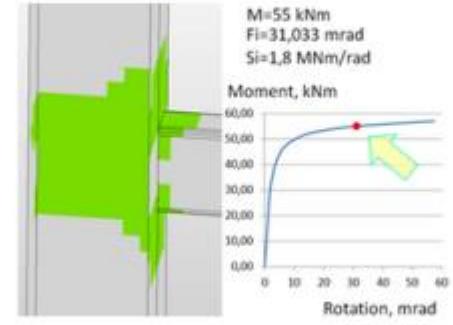
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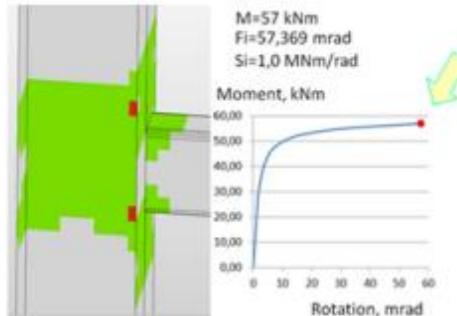


Plastification
of second flange of open section HEA

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Joint between open and hollow section

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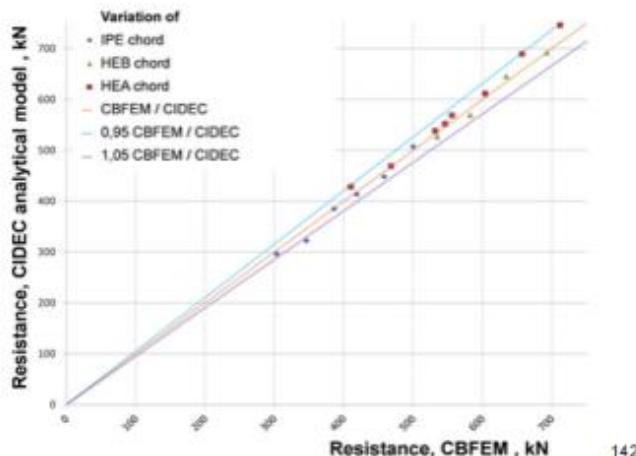
The open section web reaches design strain 5%

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Joint between open and hollow section

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Verification of resistance CBFEM to CIDEC model



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- Results shows the good accuracy of CBFEM verified to CM
- For higher stiffness / resistance / deformation capacity CBFEM compare to CM verification by research FEM validated to experiments

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„Verification
deals with mathematics;
validation
deals with physics“

Roache P.J. (1998) Verification and validation in computational science and engineering, Hermosa Publishers Albuquerque, NM.

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→ Summary



- CM in tables and tools limits poor design by incompetent amateurs
- CBFEM allows properly analysed/checked
 - Complex design solutions
 - Complicatedly loaded joints
 - **By well-trained experts**

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- Benchmark cases
and correct use of V&V
limits the improper use of model
- The high-quality education
the background
of design of pretty structural connections

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**Hierarchy of benchmark studies
for structural steel joints**

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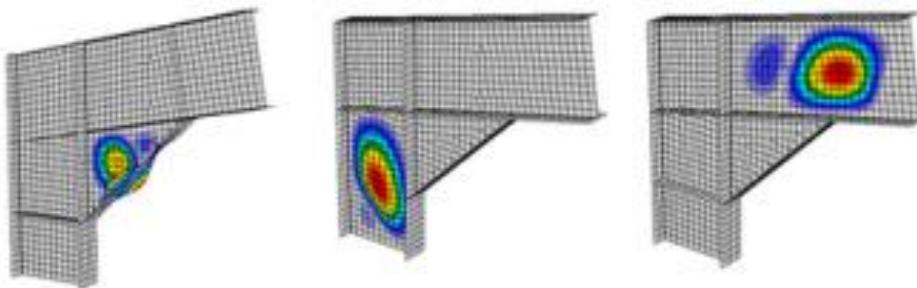
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Background references

Component based FEM

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URL: www.ocel-drevo.fsv.cvut.cz



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