Background

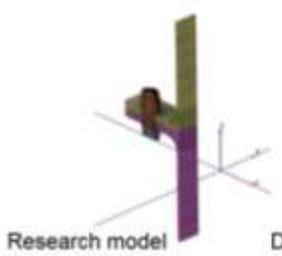
of

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

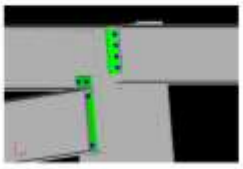


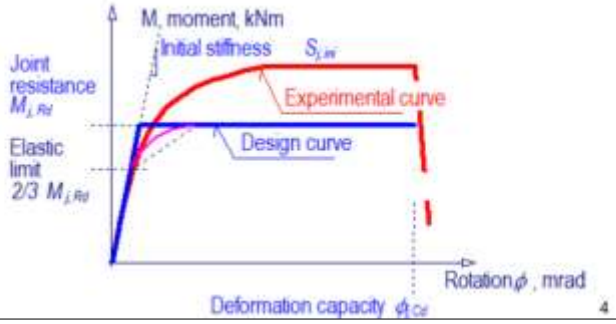
List of contents

Description of behaviour for design by moment-rotation characteristic

Connection exposed to bending

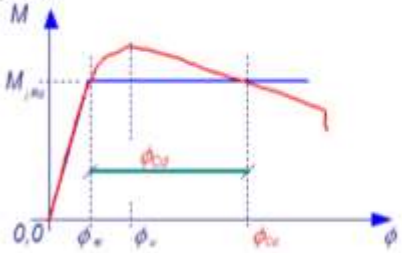
- Rotational stiffness
- Moment resistance
- Rotation capacity





Deformation/rotation capacity

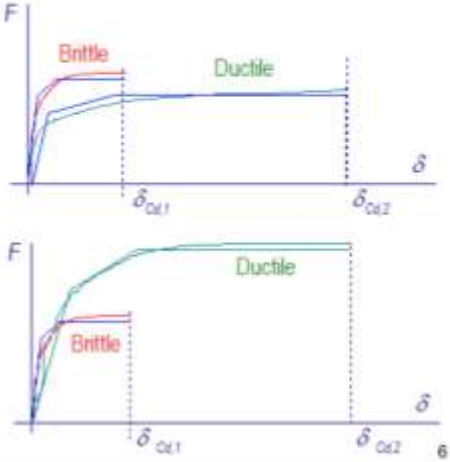
- **For safety**
  - Seismic design
  - Plastic global analyses



- Ductile components
  - Plate in bending
  - Column web in shear
- Brittle components
  - Bots, welds

Rotation capacity Upper material properties

- Question of the **Actual yield strength**



Joint design European standards

- EN1993-1-8, Eurocode 3, **Design of steel structures, Part 1-8, Design of joints**, CEN, Brussels, 2006.
- EN1994-1-1, Eurocode 4, **Design of composite steel and concrete structures, Part 1-1, General rules and rules for buildings**, CEN, 2010.

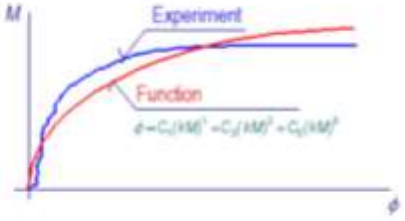
Design approaches for structural joints

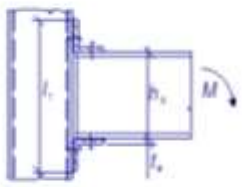
Models

- Experimental
- Curve fitting
- Analytical
  - Component Method **CM**
- Finite element analysis
  - Research
  - Design finite element analysis
    - Component based finite element method **CBFEM**

Curve fitting model

- Based on
  - **Physical experiments**
  - Component method – databases
  - Surrogate models – numerical experiments



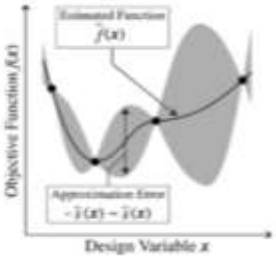


  - Optimization

Surrogate models

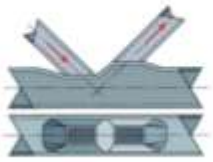
(Meta models)

- Numerical experiments
- Standardised mathematical procedure



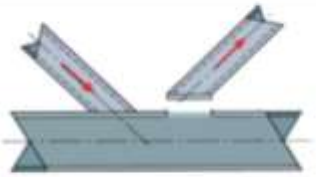
Hollow section joints

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

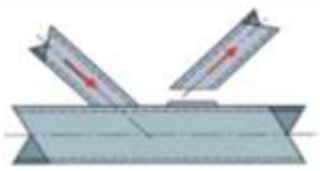


Mode A:
Plastic failure of the chord face

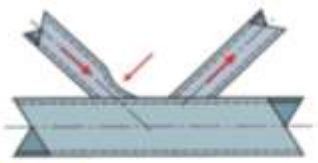
Hollow section joints



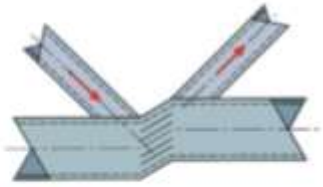
Mode B: Punching shear failure of the chord face



Mode C: Tension failure of the web member

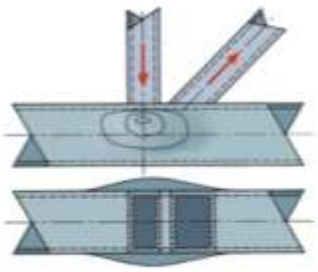


Mode D: Local buckling of the web member

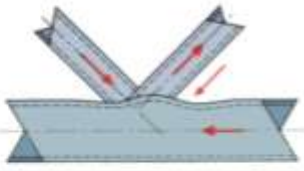


Mode E: Overall shear failure of the chord

Hollow section joints



Mode F: Local buckling of the chord walls



Mode G: Local buckling of the chord face

CIDECT materials

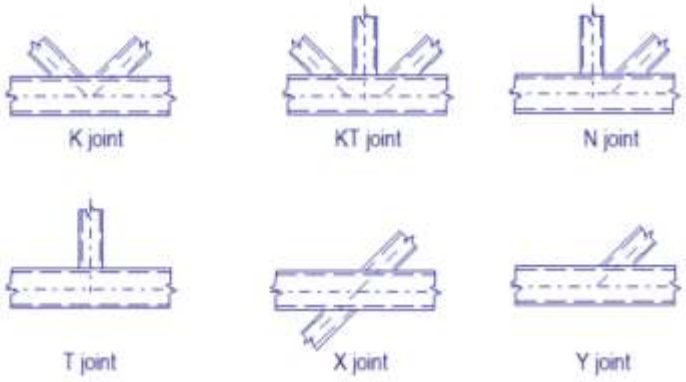
- Background CIDECT materials
  - ISO/FDIS 14346
  - EN 1993-1-8 Chapter 7
- Uni-planar and multi-planar joints
  - Circular, square or rectangular hollow sections

+

- Uni-planar joints
  - Combinations of hollow sections with open sections
- Detailed application rules to determine the static resistances of joints in lattice structures

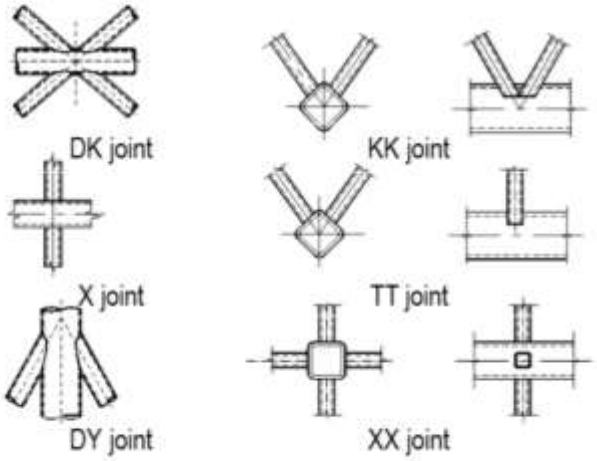
ISO/FDIS 14346: *Static Design Procedure for Welded Hollow Section Joints – Recommendations*, ISO, IIW XV-1439-13, 2012.

Geometrical types of basic joints

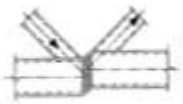
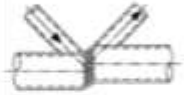
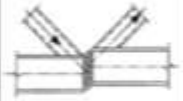


- Class 1 and 2 cross sections
- Limits in geometry

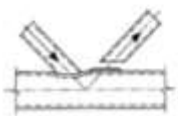
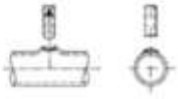
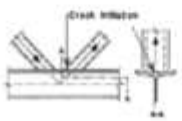
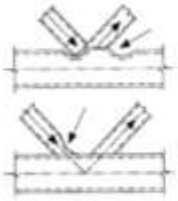
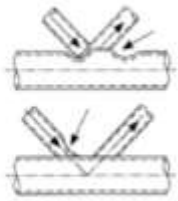
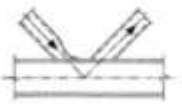
Geometrical types of complex joints



Failure modes – chord, shear

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

Failure modes – brace

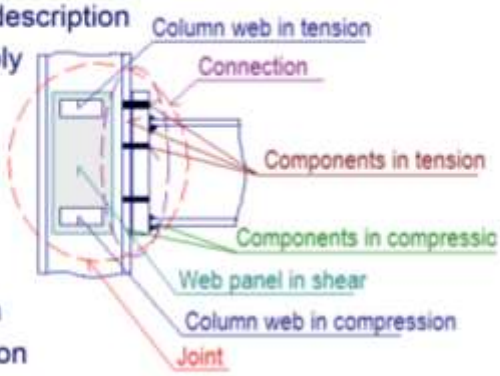
	Rectangular	Circular	Chords of I or H
Brace failure			
Local buckling			

Component based aproach for holow section design

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

Component model Procedure

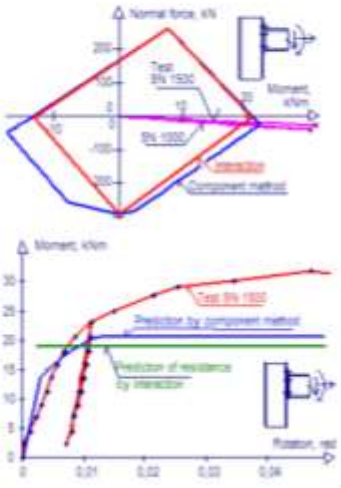
§ Decomposition of joint
§ Component description
§ Joint assembly



§ Classification
§ Representation
§ Modelling in analyses

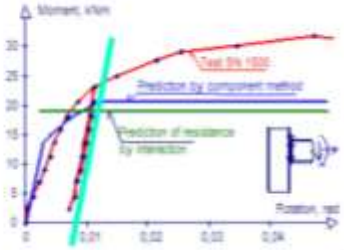
Component model Prediction accuracy

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



Component model
Prediction accuracy

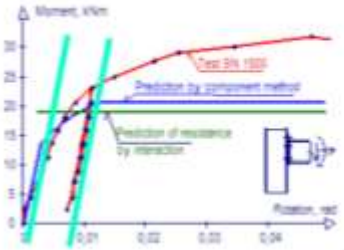
- Good accuracy
- M-N Interaction
  - Tests in Prague



Component model
Prediction accuracy

Introduction
Connection design
Models
Hollow sections
Component method
FE analyse
Validation and verification
Component based FEM
Slender plates
Bolted joints
Connection behaviour
Open sections
Hollow sections
Summary

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



Component Model
Application

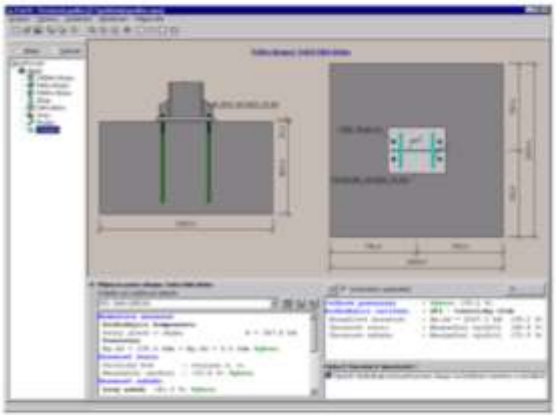
§ Design tables
  § Green book
  § Blue book

§ Computer programs

§ Simplified hand calculation

Component Model Design tools

- For limited cases



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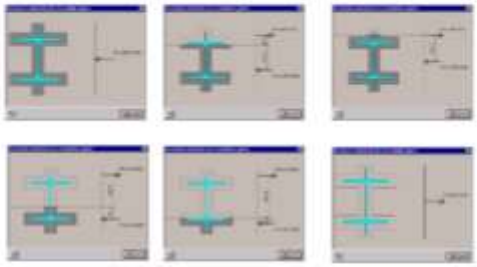
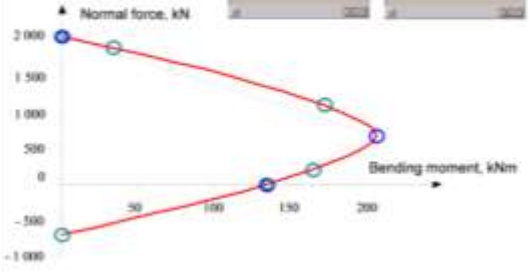
Component Model Design tools

- For limited cases





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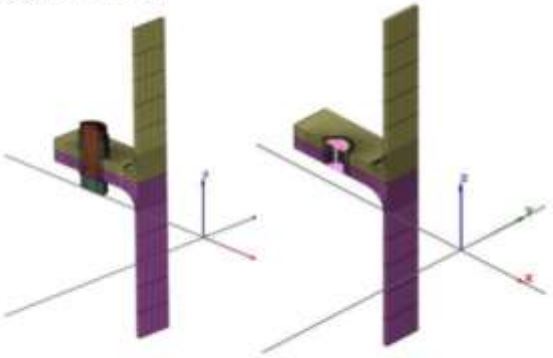
Component model Background references

- 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.
- Jaspart J.P., **Design of structural joints in building frames,** Prog. Struct. Engng Mater., 4, 2002, 18–34.
- Wald F., Sokol Z., Steenhouis M. and Jaspart, 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.

Finite Element models of joint

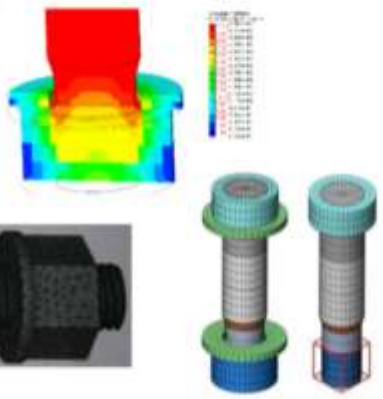
- Research oriented
- Design oriented



Research model Design model

Bolt
FEM research models

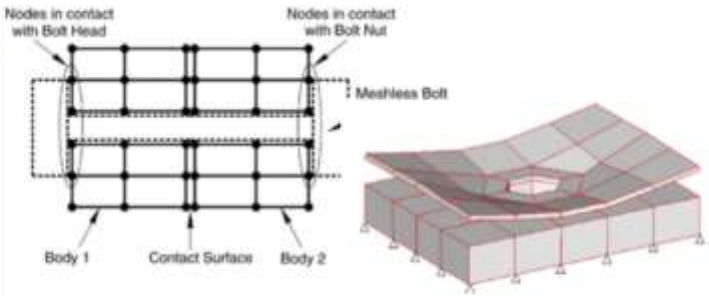
- 3D
- Complex
- Material
  - Plasticity criteria
  - Demage model



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.

Bolts
FEM design models

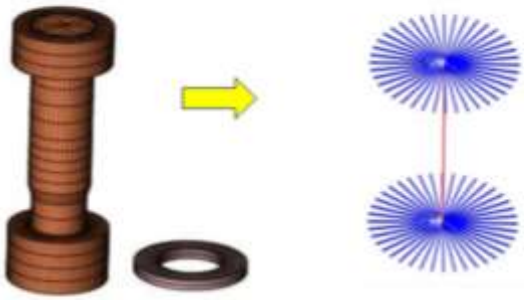
- Contact model
  - Matricks description



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

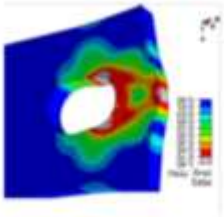
FEM modelling of bolts
Bolts

- Fan model



Bearing
FEM modelling

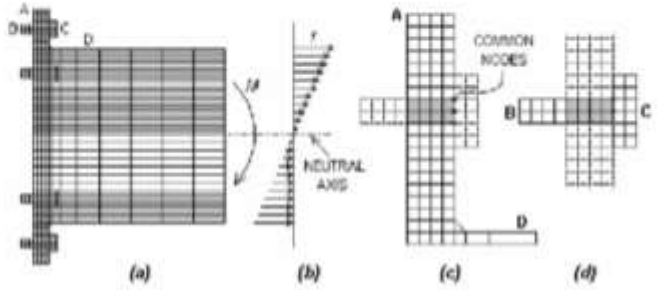
- von-Mises yield criterion
- Demage models



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

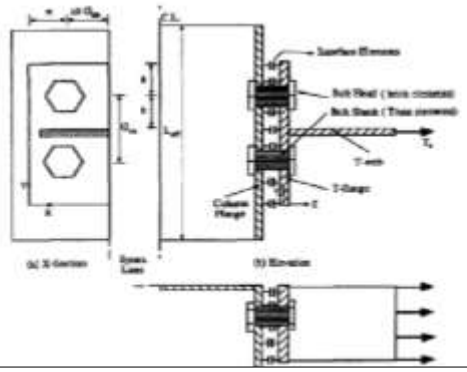
Connections
FE research models

- **N. Krishnamurthy (1978)**
  - 3 models
  - 2D model



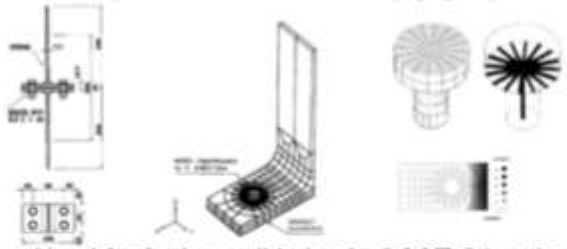
Connections
FE research models

- **Bahaari and Sherbourne (1996)**
  - 6 tests, 3D finite element model using ANSYS
  - **One of first component based finite element models**



Connections
FE research models

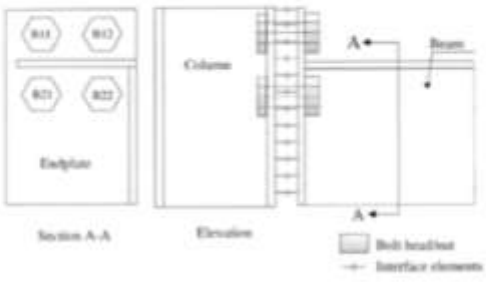
- **Bursi and Jaspart (1998)**
  - T-stub and Extended end-plate moment
  - LAGAMINE, a finite element research software
  - Bursi O. S., Jaspart J. P. Benchmarks for Finite Element Modelling of Bolted Steel Connections *Journal of Constructional Steel Research* 43 (1-3), 1997, 17-42



  - Used for further validation in COST C1 action
  - 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.

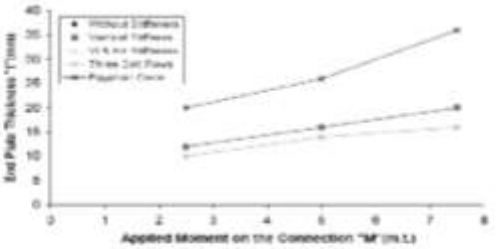
Connections
FE research models

- **Bahaari and Sherbourne (1999)**
  - 3D model
  - 4 tests



Connections
FE research models

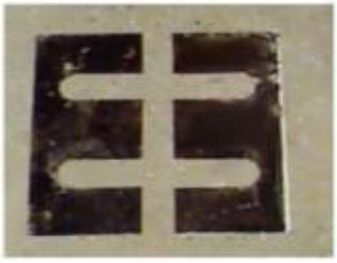
- **N.K. Hassan (2004)**
- 2D finite element modeling

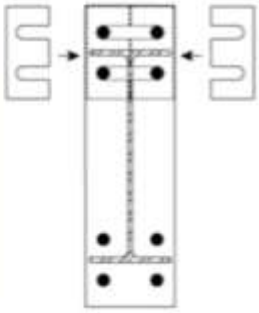


Effect of Stiffener Position on the End-Plate Thickness for a Beam section IPE 300

Connections
FE research models

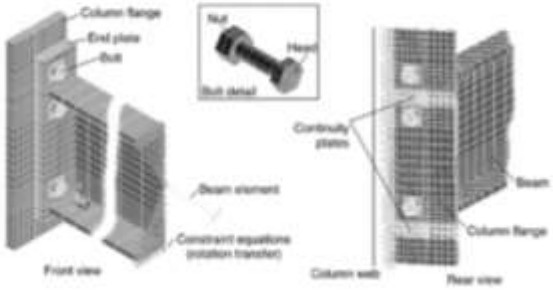
- **Emmett A. Summer (2003)**
- 12 tests, cycling load
- 3D finite element modelling
- Models of finger shims





Connections
FE research models

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



Connections
FE research models

- **Gang Shi, Yougjiu Shi, Yuanqing Wang, M.A.Bradford (2008)**
- 3D finite element modeling
- 6 experiments

Validation and verification procedures

- Well developed in FEM theory
- To check the physical accuracy
- To check the proper use
- To check the asked design level

Definitions
of Verification & Validation

Validation

compares the numerical solution with the experimental data.

Validation can be practically split into three tasks:

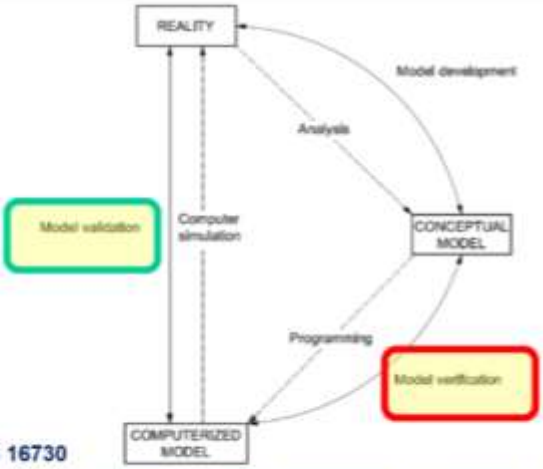
- to detect and separate the model's significant discrepancies,
- to remove and reduce removable and unavoidable errors,
- to evaluate uncertainties in the results.

Verification

uses comparison of computational solutions with highly accurate (analytical or numerical)

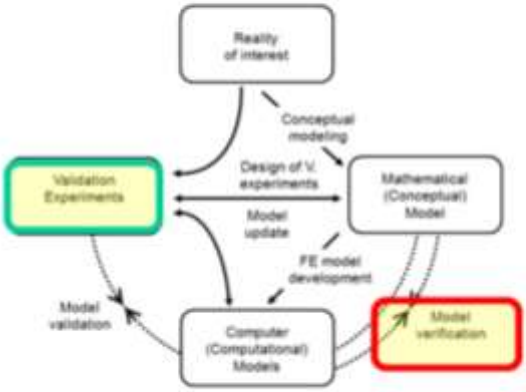
Verification is supposed to deliver evidence that mathematical models are properly implemented and that the numerical solution is correct with respect to the mathematical model.

Definitions of Verification & Validation



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

General Aspects of Modeling



Kwasniewski L. (2009) On practical problems with verification and validation of computational models, Archives of Civil Engineering, LV, 3, 323-348.

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."

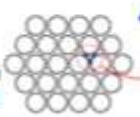
http://www.defenseindustrydaily.com

$120 million F-22 Raptor

Famous warning
Sinking offshore platform Sleipner A

- 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

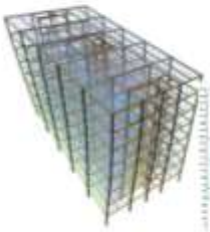
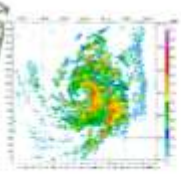

- Inaccurate finite element approximation
- **Linear elastic model of the tricell NASTRAN**
- Shear stresses underestimated by 47 %
- Certain concrete walls not thick enough




- Total economic loss of about $700 million

http://www.ima.umn.edu/~arnold/disasters/sleipner.html

What are the predictive capabilities of our computer simulations?


Modeling electronic systems e.g. Verilog

Computational Science and Engineering (CS&E) Computational Engineering and Physics (CE&P)

Numerical weather prediction

Numerical models in economics

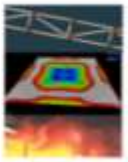
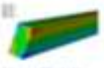
VERY GOOD

POOR

Computational Science and Engineering (CS&E)

Predictive Capabilities



Linear FE dynamic analysis

Nonlinear static (stability)

Structural Fire Engineering

Linear FE static analysis

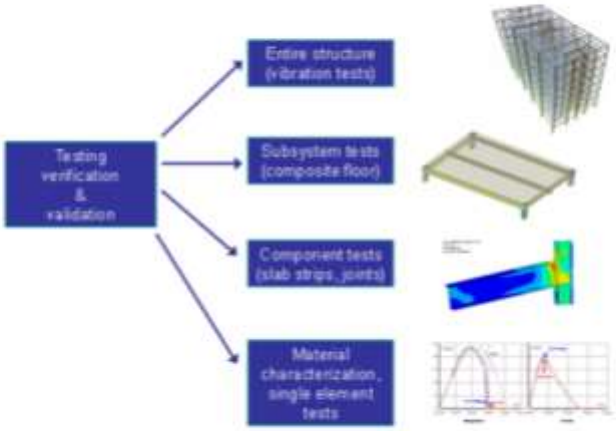
Transient dynamics (crash tests)

Computational Fluid Dynamics CFD

BETTER

MORE DIFFICULT

Hierarchy validation and verification



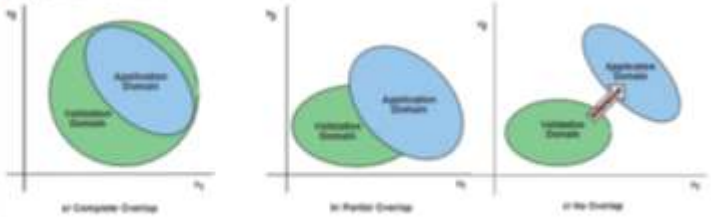
System response quantity SRQ

- 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

Validation domains

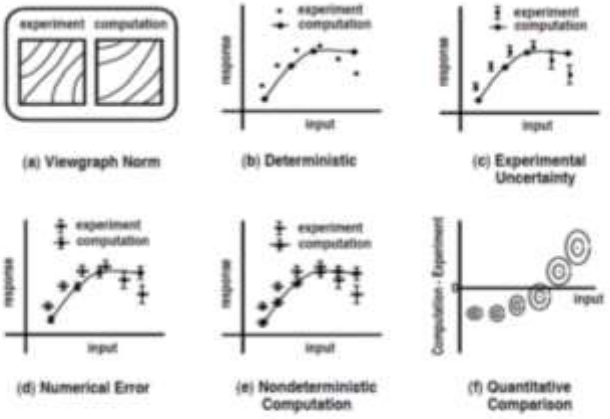
Application domain
defines the intended boundaries for the predictive capability of the computational model

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

Validation metrics



(a) Viewgraph Norm (b) Deterministic (c) Experimental Uncertainty

(d) Numerical Error (e) Nondeterministic Computation (f) Quantitative Comparison

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.

Evaluation of Mechanical Structural Response

- **Local quantities**
  - Stresses
  - Internal forces
  - Larger uncertainties especially
- **Global quantities**
  - Deflection
  - Whole (or a large part) of structure
  - Boundary condition

Verification - Mesh density study

- Discretization error $E = f_h - f_{exact} = Ch^p + H.O.T.$
- Order of convergence $p = \frac{\ln\left(\frac{f_3 - f_2}{f_2 - f_1}\right)}{\ln(r)}$
- Estimate of the asymptotic solution

$$f_{h=0} \cong f_1 + \frac{f_1 - f_2}{r^2 - 1}$$

- E_1 is the estimator of the relative error

$$E_1 = \frac{\varepsilon}{r^p - 1} \qquad \varepsilon = \frac{f_1 - f_2}{f_1}$$

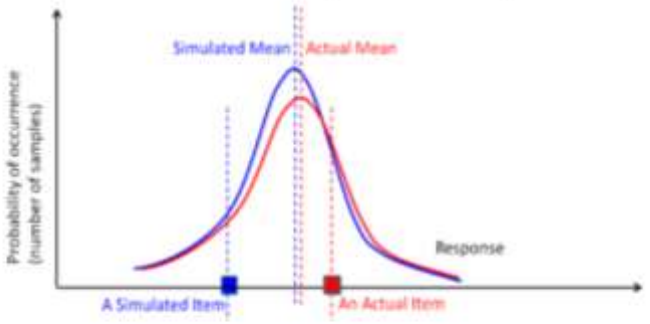
- **Grid Convergence Index** – GCI procedure (Richardson extrapolation)

$$GCI = \frac{F_s|\varepsilon|}{r^p - 1} 100\%$$

Roache P.J., Verification and validation in computational science and engineering, Computing in Science Engineering, Hermosa pub., 1988, 8-9.

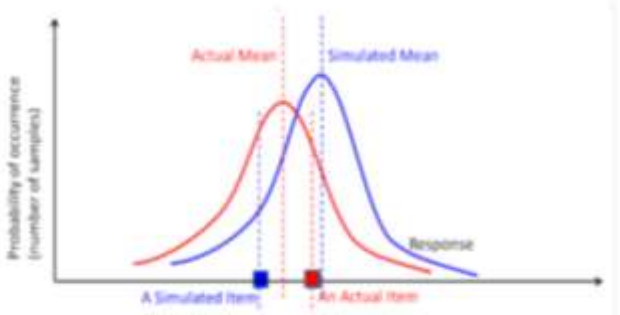
Verification and Validation of Computer Simulations

FE model well replicates the experiment



Verification and Validation of Computer Simulations

Effect of calibration



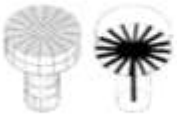
Databases of benchmark problems

- **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

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.



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

Verification and Benchmark cases

Chapters

Description

2 Component method

CBFEM

4 Force-deformation curve

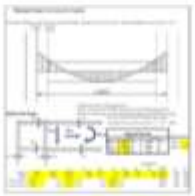
5 Global behaviour

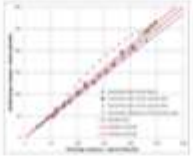
6 Verification of resistance

Global verification

Initial stiffness, Resistance, Deformation capacity

8 Benchmark case



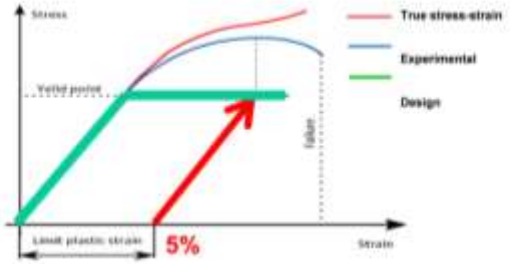


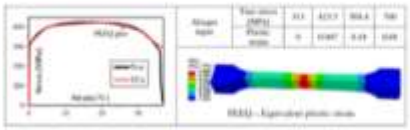
Component based FEM

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

Material for FE design model

- Bilinear ideal elastic-plastic model

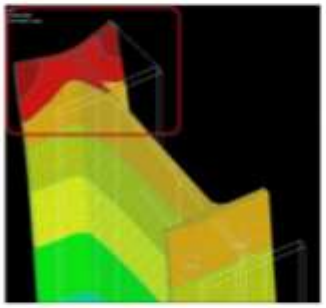




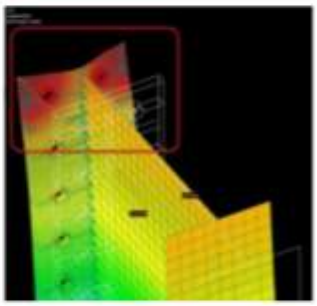
Mute P., Beg D., A complete study of bearing stress in single bolt connections, JCSR, 9 5 (2014) 126–140

Plate modelling

3D – bricks



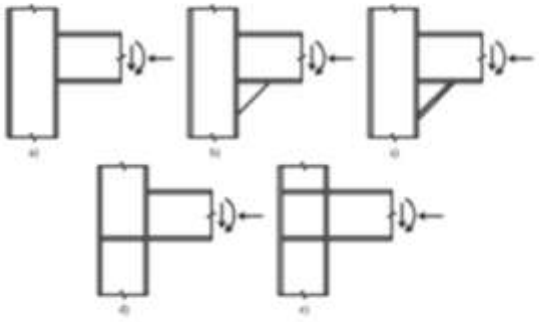
2D elements - shells



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

Design model
Slender plate in compression

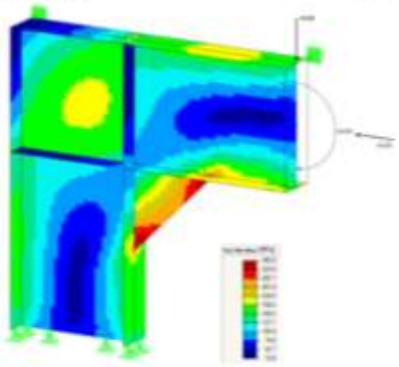
- Column web
- Stiffeners



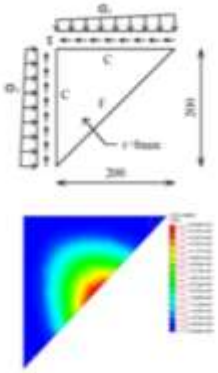
FE research model
on T triangular stiffener

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

In frame

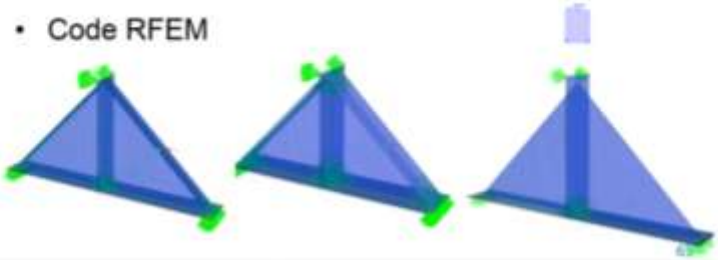


at a separate element



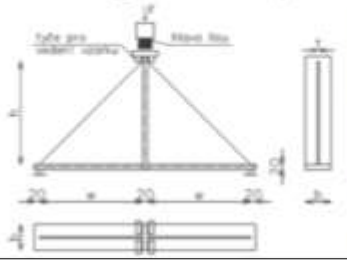
Research FEM

- 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



Experimental research

- 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



Supports and loading

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

Stiffener with free edge

h = 400 mm, w = 200 mm, t = 6 mm

Stiffener with free edge

$h = w = 400$ mm, $t = 4$ mm and $t = 6$ mm



Stiffener with partial stiffened edge

h = w = 400 mm, t = 6 mm, $t_f = 6$ mm, $b_f = 60$ mm



Stiffener with partial stiffened edge

h = w = 400 mm, t = 6 mm, $t_f = 12$ mm, $b_f = 120$ mm

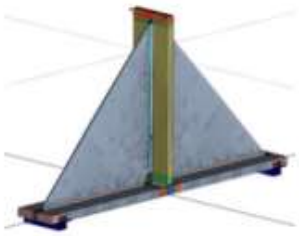


Stiffener with partial stiffened edge

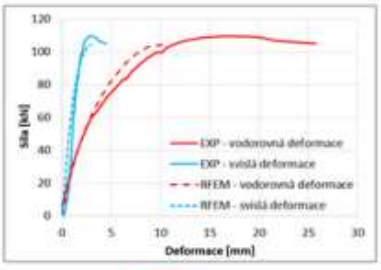
h = w = 400 mm, t = 4 mm, t_f = 12 mm, b_f = 120 mm

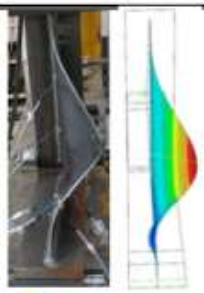


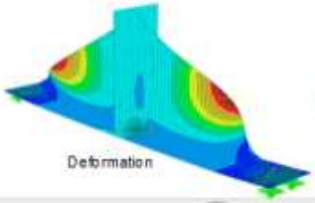
- Validation on force-deformation curve *F-δ* for resistance
- Vertical deformation at centre
- Vertical deformation at max. amplitude

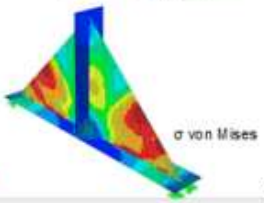



Validation of research model Free edge

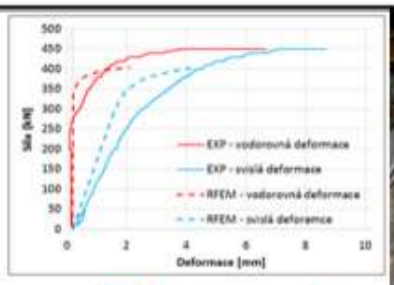


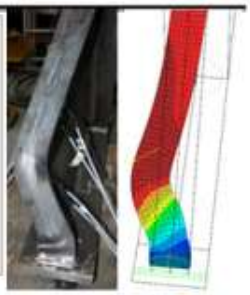


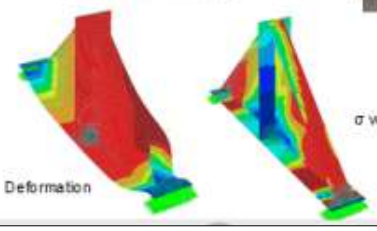




Validation of research model
Partial stiffened edge





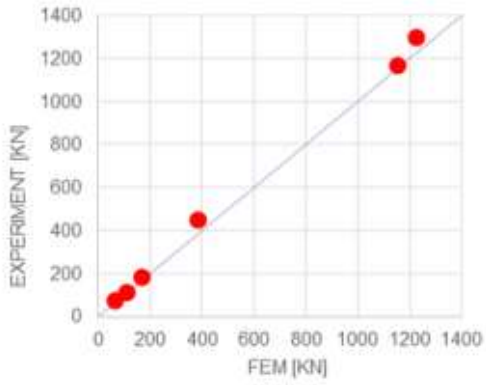


σ von Mises

Deformation

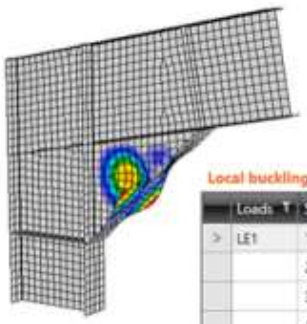
Validation of FE research model
on T triangular stiffener tests

- Validation of reserch FEM model for resistance



Design model of
slender plate in compression

- Buckling analysis

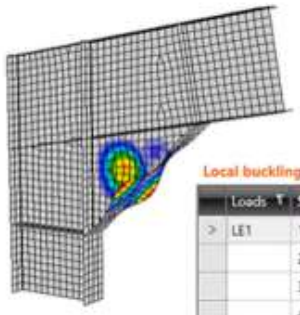


Local buckling of joint

	Loads	Shape	Factor
>	LE1	1	4,18
		2	4,44
		3	4,76
		4	5,04
		5	5,08
		6	5,44

Design model of slender plate in compression

- Buckling analysis



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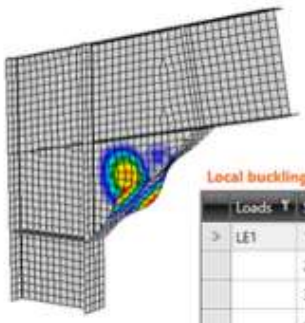
Introduction
Connection design
Models
Hollow sections
Component method
FE analyse
Validation and verification
Componentbased FEM
Slender plates
Bolted joints
Connection behaviour
Open sections
Hollow sections
Summary

Design model of slender plate in compression

- Buckling analysis



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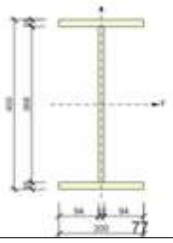

Introduction
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Summary

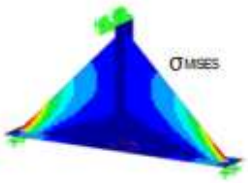
Design model Slender plate in compression

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 $\frac{\rho \cdot \alpha_{ult,k}}{\gamma_{M1}} \geq 1$

Design model
Slender plate in compression

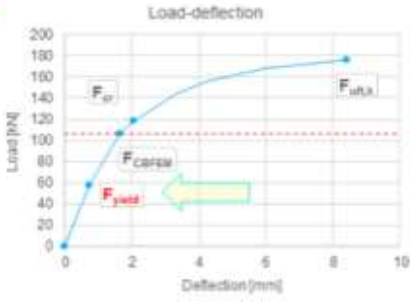


$\sigma_{MISES} = f_y$

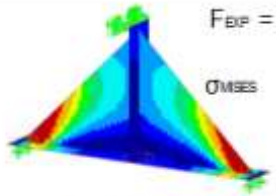
F = 57,6 kN

z = 0,7 mm

ε = 0,25%



Design model
Slender plate in compression



F_{EXP} = 109,7 kN

F = 105,8 kN

z = 1,6 mm

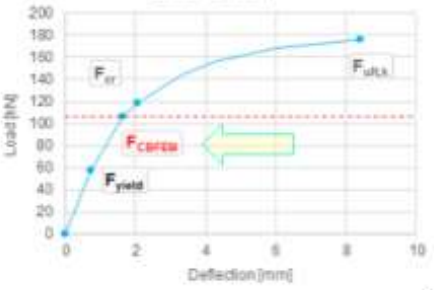
ε = 0,7%

α_σ = 1,123

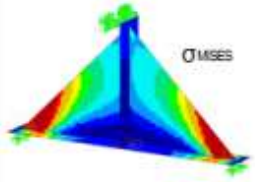
α_{ultk} = 1,659

ρ = 0,603

1,001 > 1 OK



Design model
Slender plate in compression

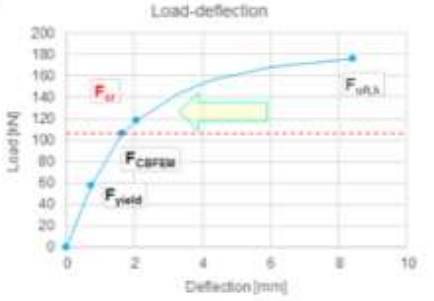


F = 118,8 kN

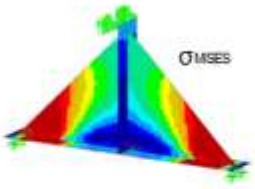
z = 2,1 mm

ε = 1%

α_σ = 1,0



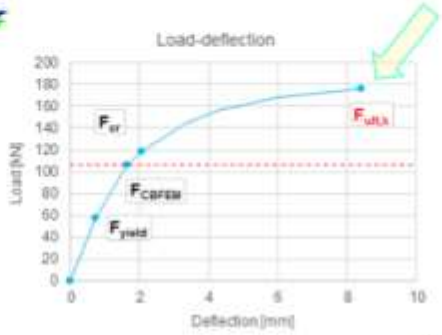
Design model
Slender plate in compression



F = 175,6 kN

z = 8,4 mm

ε = 5%



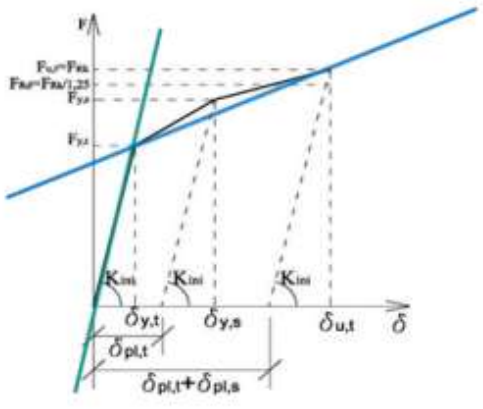
Design model
of bolted connections

- In shear
- In tension

- Nonpreloaded
  - Are preloaded
- Preloaded bolts
  - Controlled slip

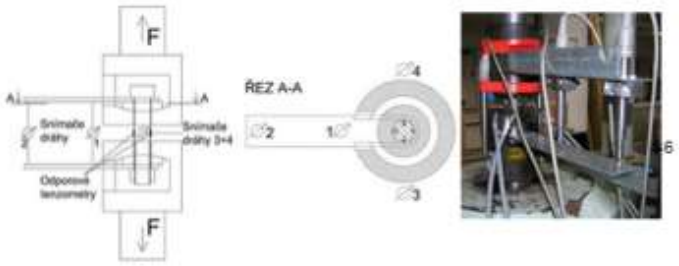
Design model of bolt in tension

- Force-displacement diagram



Bolted connection
Deformation stiffness of bolt in tension

- References from literature
- Experimental research



List of own experiments

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

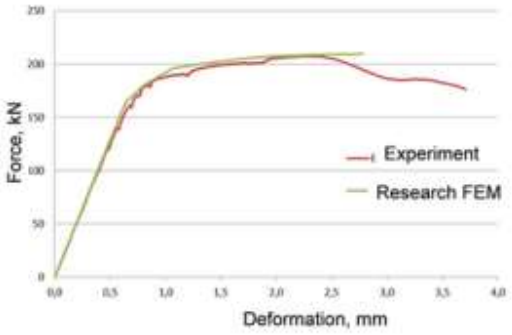
No.	Diameter	Material	Bolt length l_b	Grip length l_g	Nut height l_n	Washer height l_w	Head height l_h
			[mm]	[mm]	[mm]	[mm]	[mm]
1	M20	8.8	81.5	42.2	15	0	12.6
2	M16	10.9	109	35.4	17	2 x 4	10.1
3	M16	10.9	108.2	4	17	2x4.1	10.2
4	M16	10.9	108.2	10.5	12.7	2x4.1	10.2
5	M20	8.8	57.7	32.9	15.1	0	12.6
6	M20	8.8	0	99.3	15.6	3.1+3.2	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

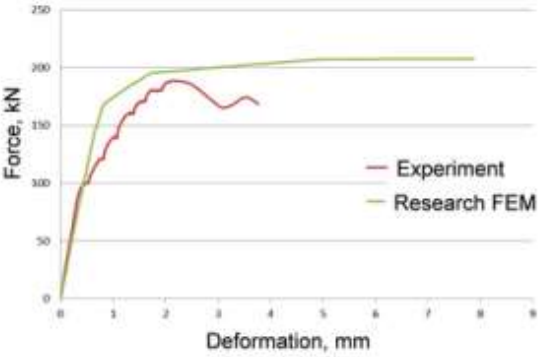




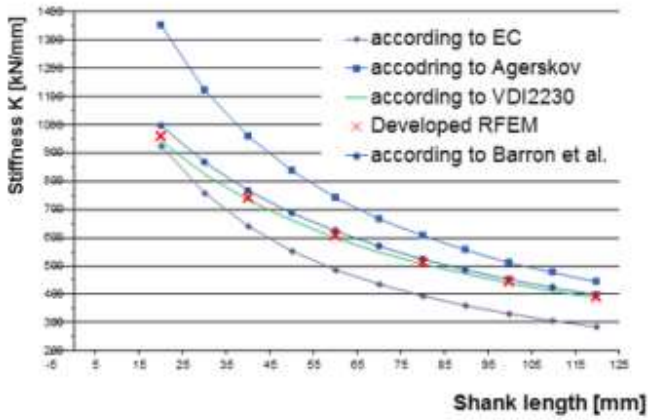

Validation for rupture of thread



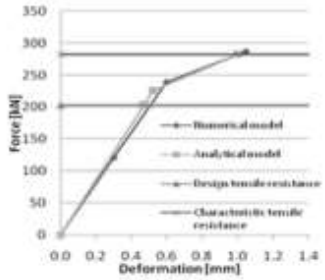
Validation for tearing down of nut

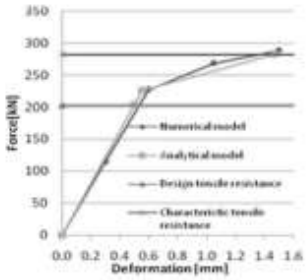


Parametric study of the bolt tensile stiffness



Verification of design model of bolt in tension





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

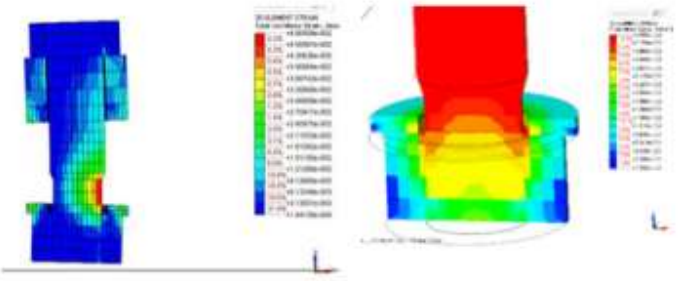
Bolts M24 grade 8.8

Modelling of T stub behaviour

- Research model
  - Validation
- Design model
  - Verification

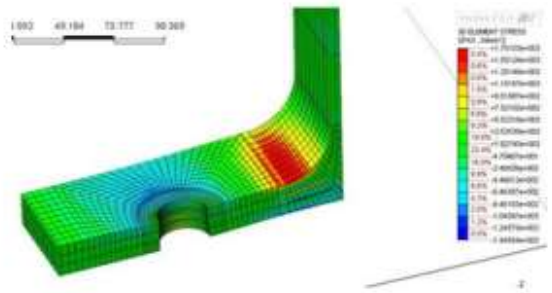
Bolts research model

- Unequal stresses distribution in the threaded part of the bolt



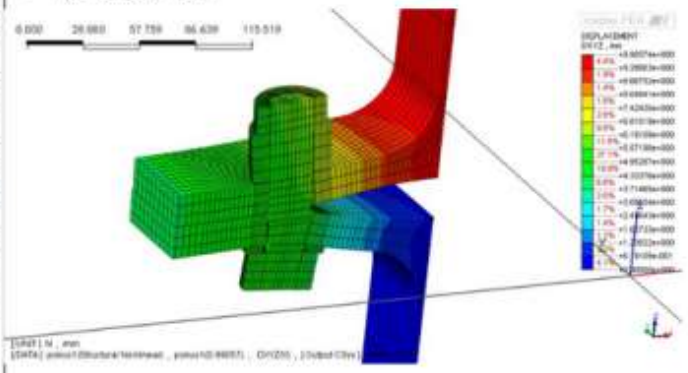
T stub behaviour
Research FE model

- Mesh sensitivity

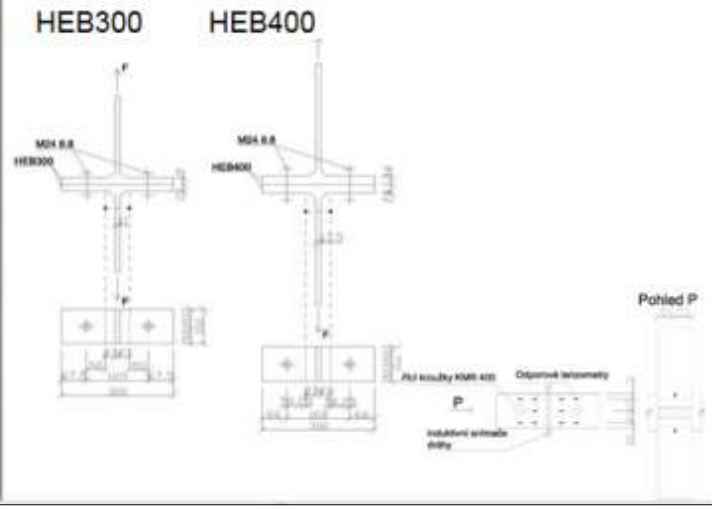


T stub behaviour
Research FE model

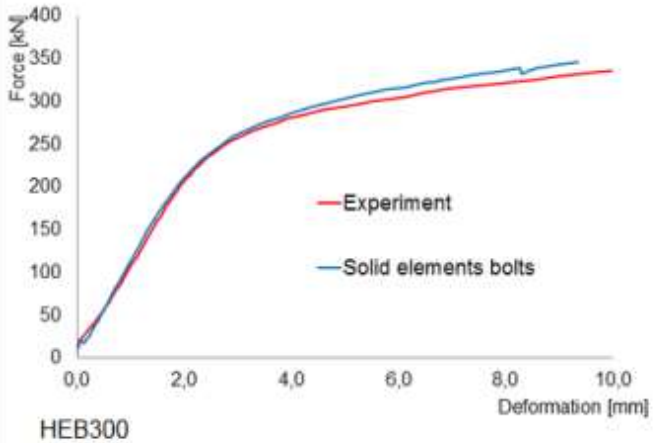
- Bending of bolt
- MIDAS FEM



Experiment with T stub



Validation – global deformation



HEB300

Validation – local deformation

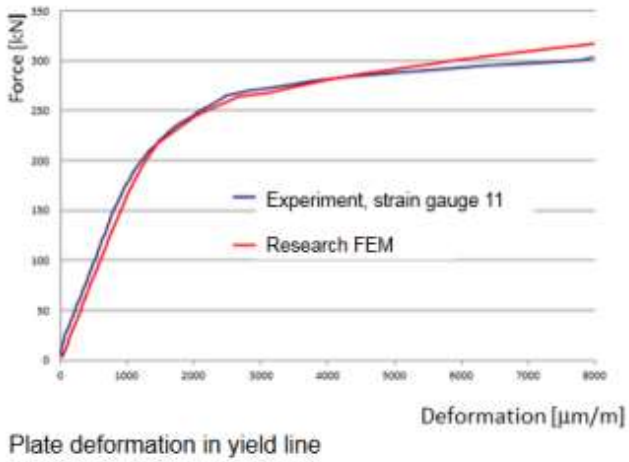


Plate deformation in yield line

Validation – local deformation

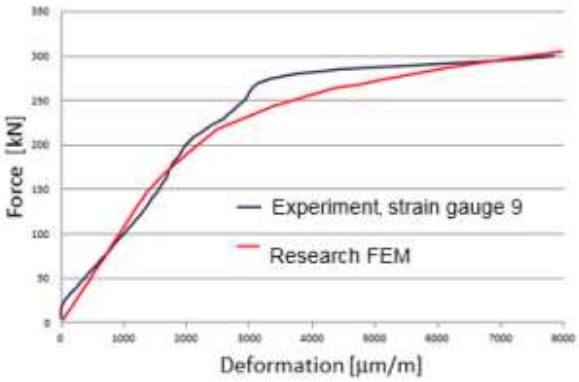
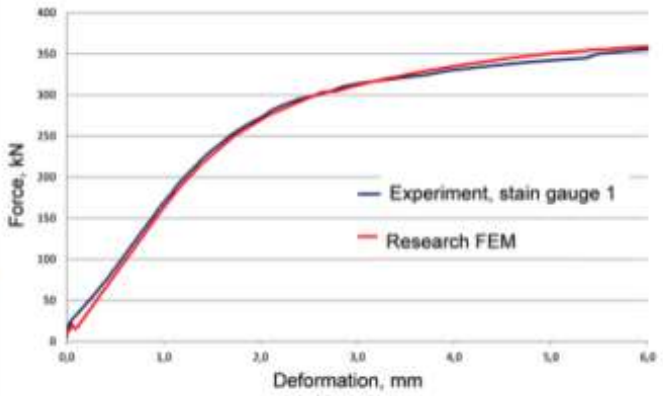


Plate deformation in yield line

Experiment with T stub

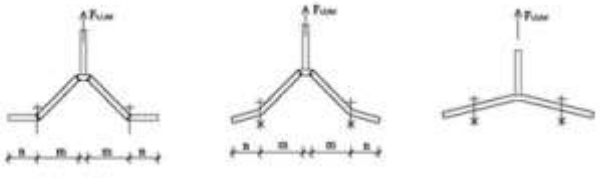
HEB400

Validation – global deformation



HE B 400

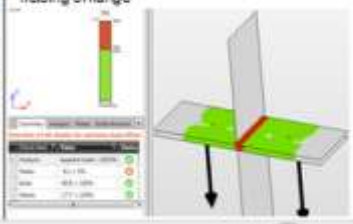
T stub design model Verification



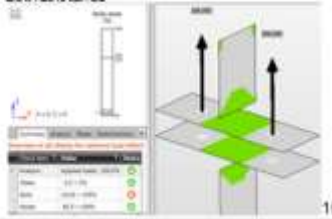
$$F_{t,1,Rd} = \frac{(8n - 2e_w)M_{pl,1,Rd}}{2mn - e_w(m+n)} \qquad F_{t,2,Rd} = \frac{2M_{pl,2Rd} + 2nF_{t,Rd}}{m+n} \qquad F_{t,3,Rd} = 2F_{t,Rd}$$

CBFEM:

Yielding of flange



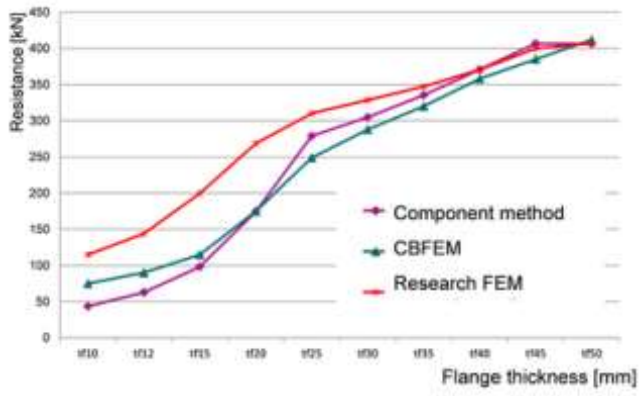
Bolt resistance



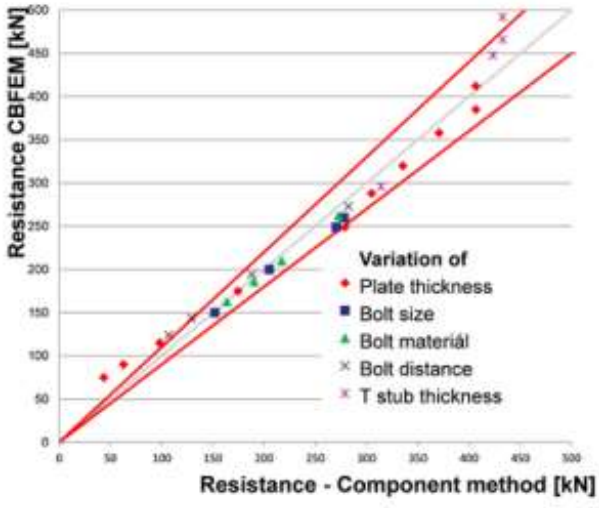
T stub design model Verification

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

T stub design model Verification



T stub design model Verification

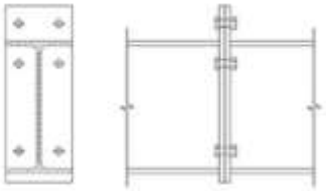


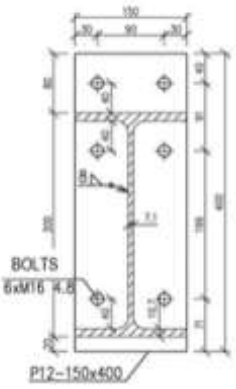
Connection behaviour bolted connections of open section

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

Verification bolts in tension and in shear

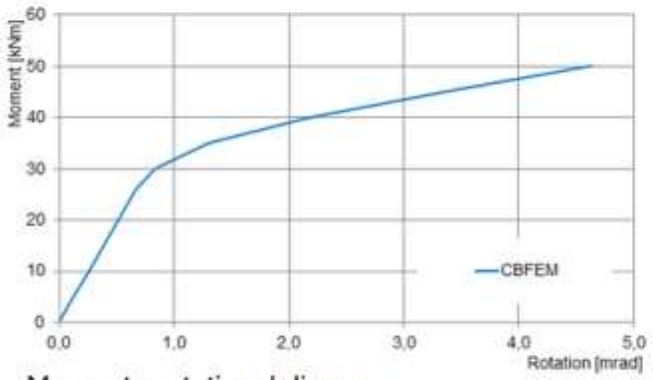
Beam splices joint





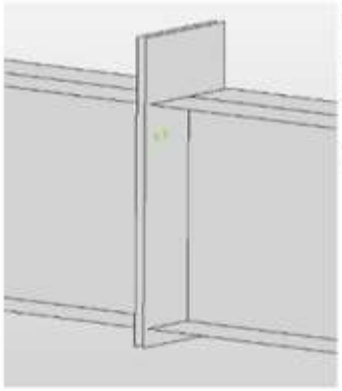
End plate connection
Steel S355
Plate 12 mm
Bolts M16 4.8

Verification bolts in tension and in shear



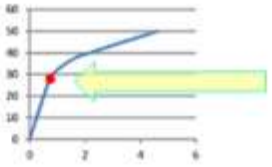
Moment - rotational diagram predicted by CBFEM and CM

Global behaviour
bolts in tension and in shear



M=28 kNm
Fi=0,746 mrad
Si=37,5 MNm/rad

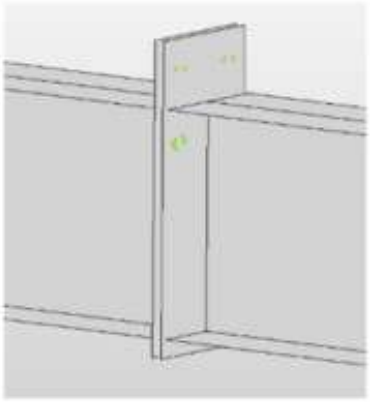
Moment, kNm



Rotation, mrad

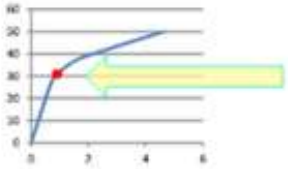
Elastic stresses

Global behaviour
bolts in tension and in shear



M=31 kNm
Fi=0,898 mrad
Si=34,5 MNm/rad

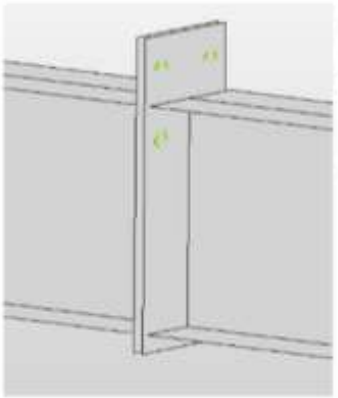
Moment, kNm



Rotation, mrad

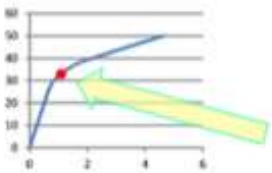
Plastification round the lower bolts

Global behaviour
bolts in tension and in shear



M=33 kNm
Fi=1,089 mrad
Si=30,3 MNm/rad

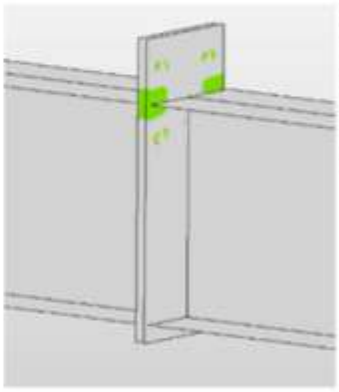
Moment, kNm



Rotation, mrad

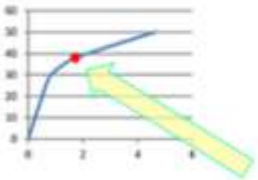
Plastification round the upper bolts

Global behaviour bolts in tension and in shear



M=38 kNm
Fi=1,714 mrad
Si=22,2 MNm/rad

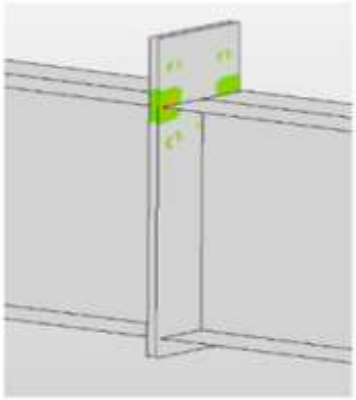
Moment, kNm



Rotation, mrad

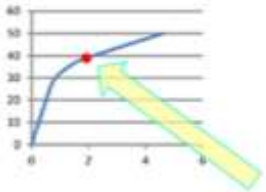
Plastification round the flanges

Global behaviour bolts in tension and in shear



M=39 kNm
Fi=1,925 mrad
Si=20,3 MNm/rad

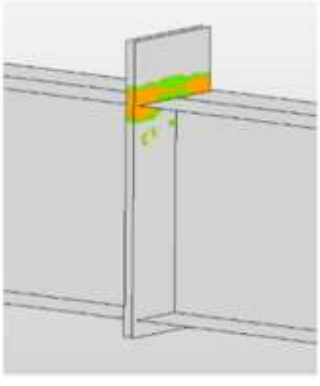
Moment, kNm



Rotation, mrad

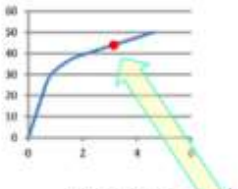
Plastification in the web of HEA

Global behaviour bolts in tension and in shear



M=44 kNm
Fi=3,138 mrad
Si=14,0 MNm/rad

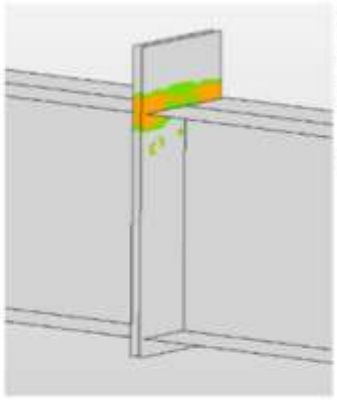
Moment, kNm



Rotation, mrad

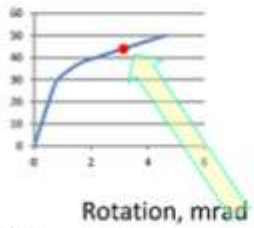
Plastification in the web of HEA

Global behaviour
bolts in tension and in shear



M=44 kNm
Fi=3,138 mrad
Si=14,0 MNm/rad

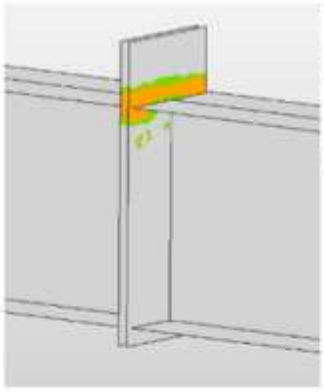
Moment, kNm



Rotation, mrad

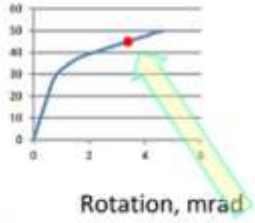
Plastification in the web of HEA

Global behaviour
bolts in tension and in shear



M=45 kNm
Fi=3,383 mrad
Si=13,3 MNm/rad

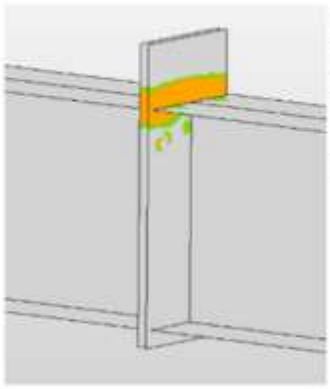
Moment, kNm



Rotation, mrad

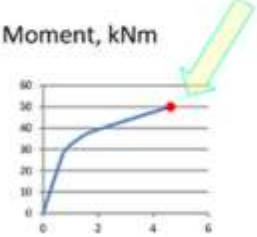
Plastification in the web of HEA

Global behaviour
bolts in tension and in shear



M=50 kNm
Fi=4,626 mrad
Si=10,8 MNm/rad

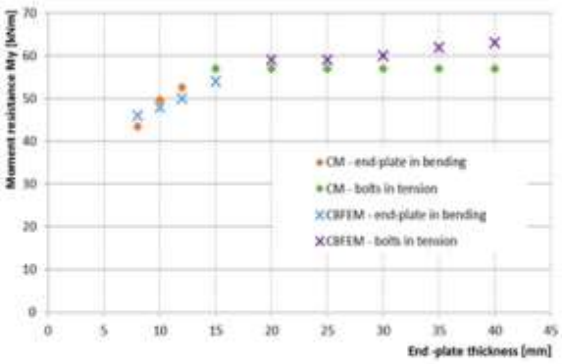
Moment, kNm



Rotation, mrad

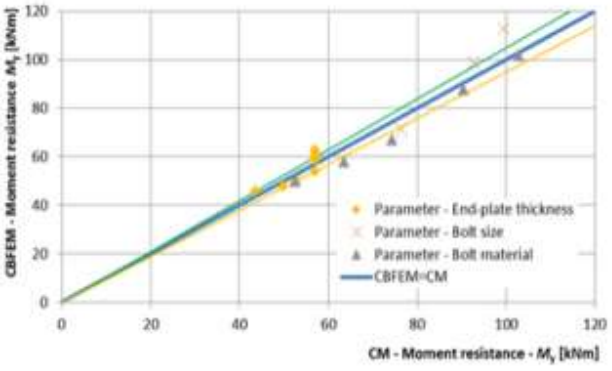
Full plastification in the web of HEA

Verification bolts in tension



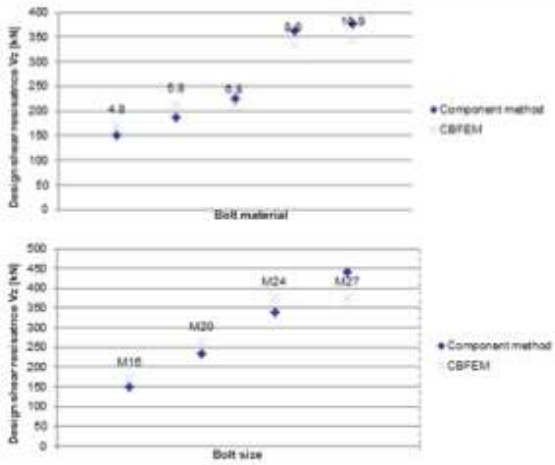
End plate thickness

Verification bolts in tension

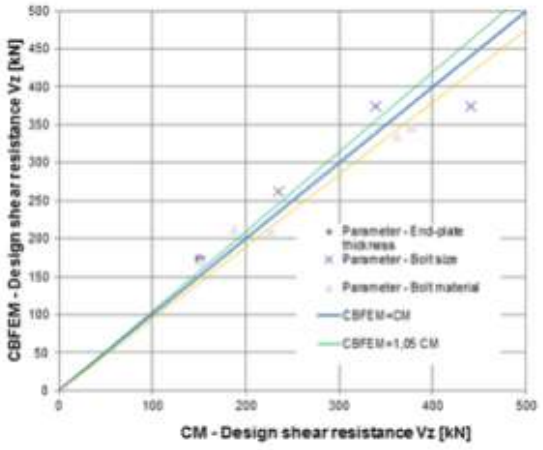


Geometrical and material parameter

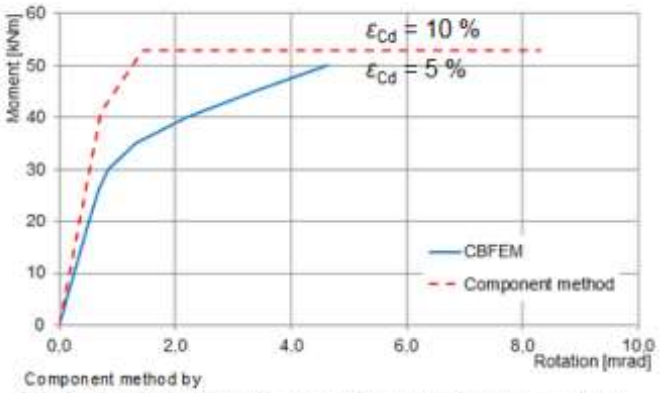
Verification bolts in shear



Verification bolts in shear



Verification deformation capacity



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.

Prediction of Deformation capacity

- Material
  - For resistence ε_{Cd} = 5 %
  - For deformation capacity ε_{Cd} = 15 %

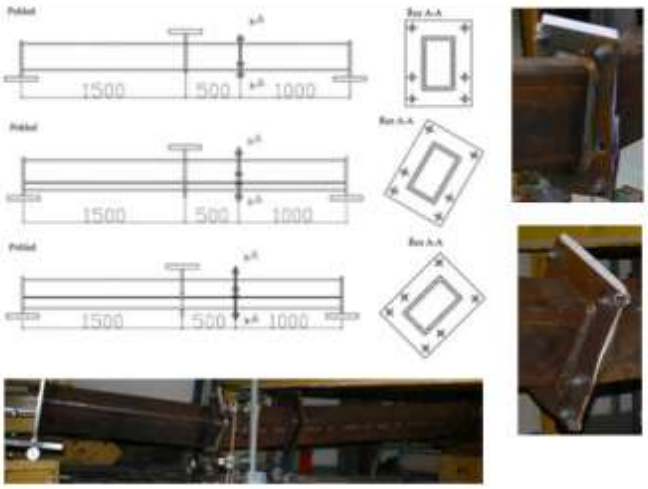
- Actual yield strength

EN 1998-1-8 cl. 6.2

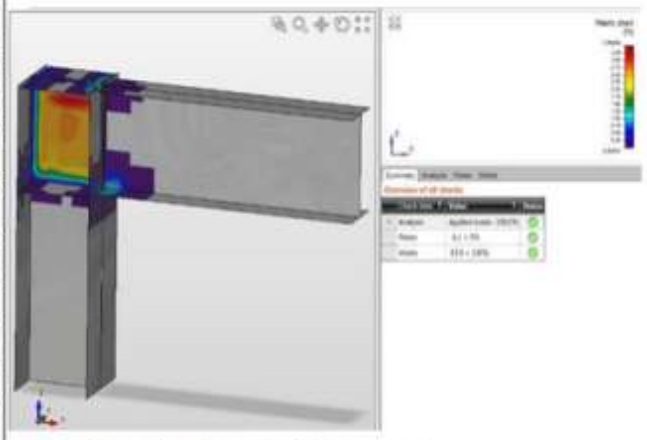
Overstrenght factor γ_{ov} = 1,25

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

Generaly loaded connections
Experiments – beam splices



Verification to component model
Welded portal frame eaves moment connection

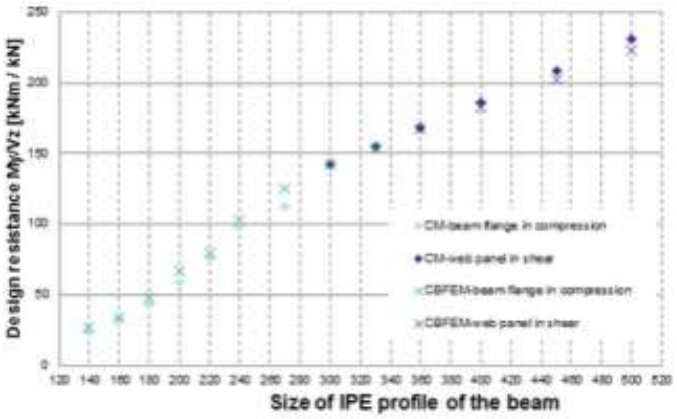


Beam IPE330 to column HEB260 connection

Verification to component model
Welded portal frame eaves moment connection

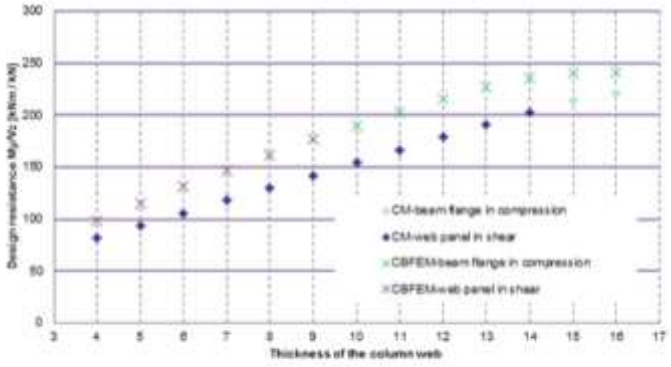
Parameter	Component method		CBFEM-Idea RS	
	Resistance [kN/kNm]	Critical component	Resistance [kN/kNm]	Critical component
IPE140	24	Beam flange in compression	27	Beam flange in compression
IPE160	33	Beam flange in compression	34	Beam flange in compression
IPE180	44	Beam flange in compression	48	Beam flange in compression
IPE200	59	Beam flange in compression	67	Beam flange in compression
IPE220	77	Beam flange in compression	90	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

Verification to component model
Welded portal frame eaves moment connection

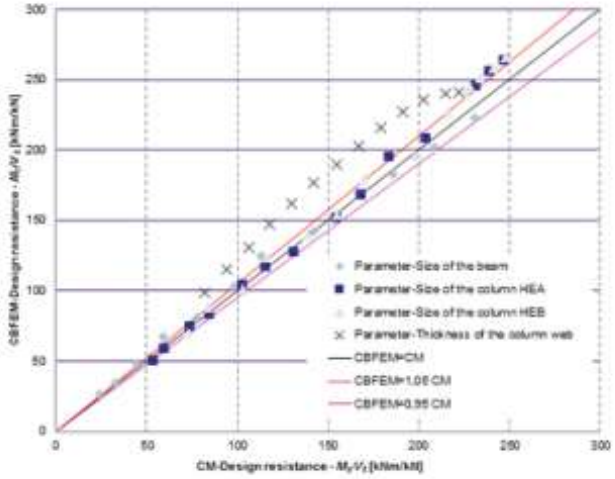


Verification to component model
Welded portal frame eaves moment connection

- Thickness of the column web



Verification to component model
Welded portal frame eaves moment connection



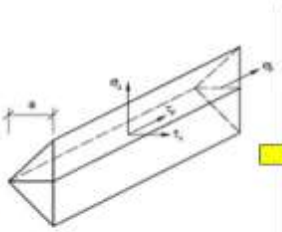
Joint between open and hollow section

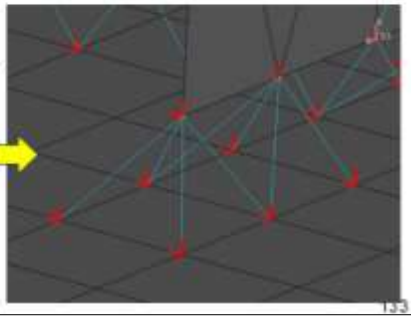
- Verification
  - Welds
  - FEM meshing

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

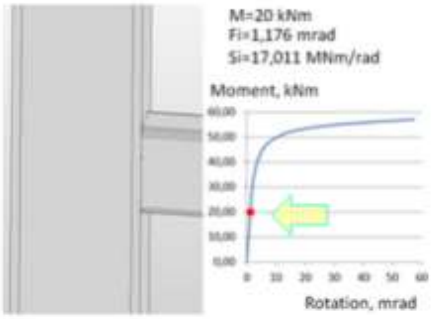
Welds for FEM design model

- **Model of weld**
  - $F_{w,Ed}$; $F_{w,Rd}$ - stiffness, resistence, deformation capacity
  - $F_{w,Ed}$ - stiffness, resistence, deformation capacity
  - $F_{w,Ed}$ - neglected



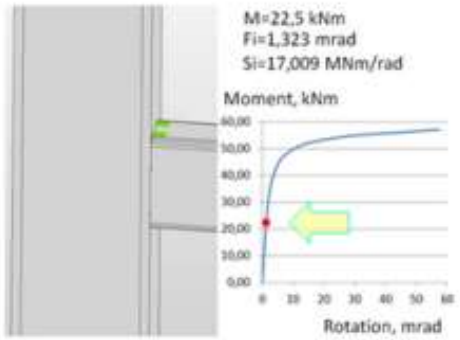


Joint between open and hollow section



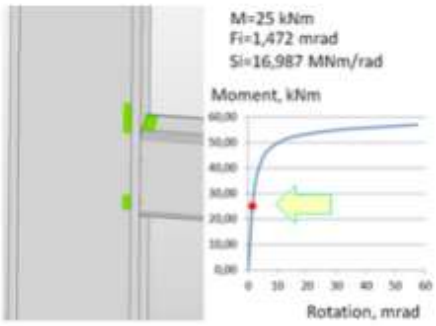
Elastic stage

Joint between open and hollow section



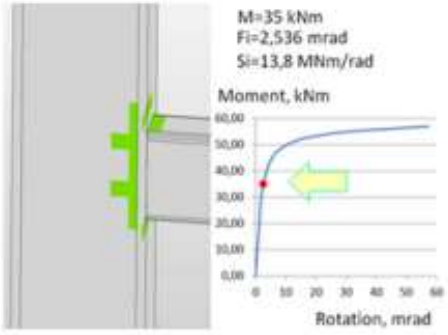
Plastification
of the hollow section RHS upper flange

Joint between open and hollow section



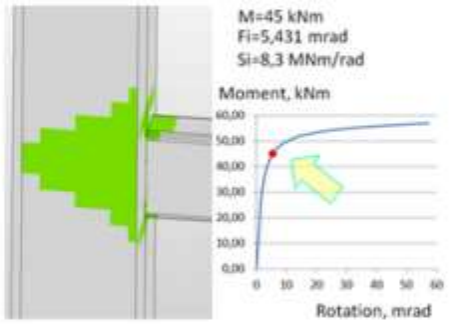
Initial plastification
in the open section web

Joint between open and hollow section



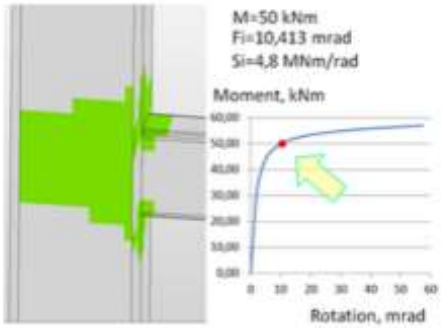
Initial plastification
in the open section flange

Joint between open and hollow section



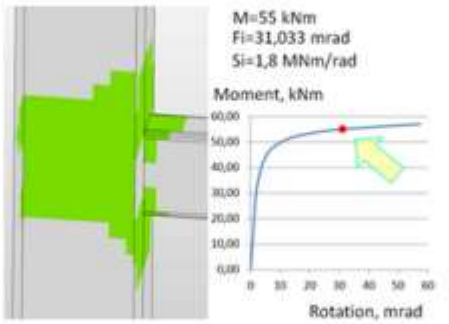
Full plastification
through the open section web

Joint between open and hollow section



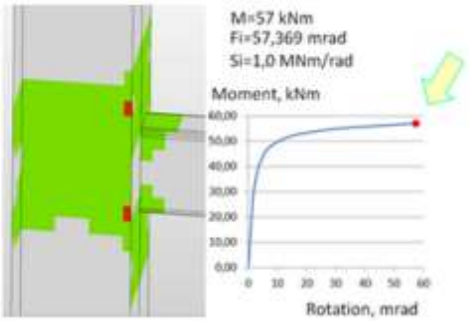
Initial plastification
in the hollow section RHS web

Joint between open and hollow section



Plastification
of second flange of open section HEA

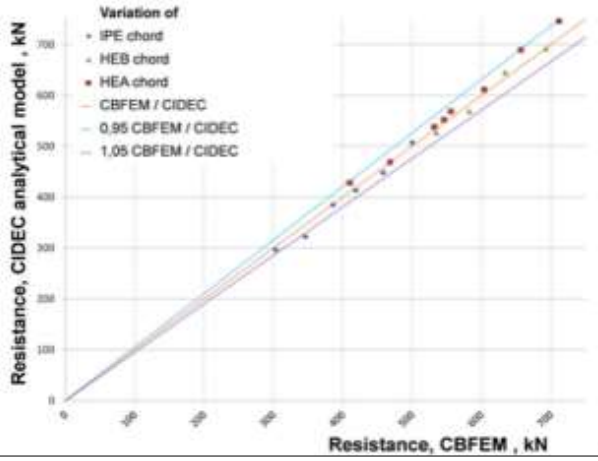
Joint between open and hollow section



The open section web reaches design strain 5%

Joint between open and hollow section

Verification of resistence CBFEM to CIDEC model



Summary

- 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

Summary

„**Verification**
deals with **mathematics**;
validation
deals with **physics**''

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

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**

Summary

- 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

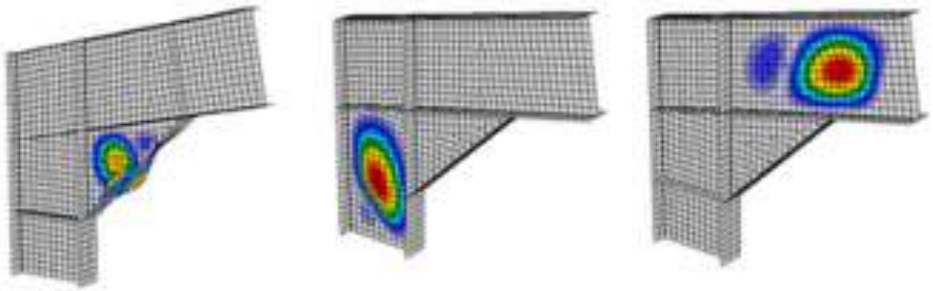
Hierarchy of benchmark studies for structural steel joints

- **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

Background references Component based FEM

- Wald, F., Gödrich, L., Šabatka L., Kabeláč, J., Navrátil, J., **Component Based Finite Element Model of Structural Connections**. *In Steel, Space and Composite Structures*. Singapore, 2014, 337-344, ISBN 978-981-09-0077-9.
- Gödrich L., Wald F., Sokol Z., **Advanced Modelling of End Plate**. In *Eurosteel 2014*. Brussels, ECCS, 2014, 287-288, ISBN 978-92-9147-121-8.
- Gödrich L., Kurejková M., Wald F., Sokol, Z., **The Bolts and Compressed Plates Modelling**. In *Steel, Space and Composite Structures*, Singapore, 2014, 215-224, ISBN 978-981-09-0077-9.
- Wald F., Šabatka L., Kabeláč J., Kolaja D., Pospíšil M., **Structural Analysis and Design of Steel Connections using Component Based Finite Element Model** (CBFEM), *Journal of Civil Engineering and Architecture*, 10/2015.

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



František Wald
Czech Technical University in Prague