Background
of
Component Based Finite Element Method

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List of contents

• Connection design
  – Models
  – FE analyse
• Validation & Verification
• Components modelling
  – Bolts
  – Slender plates
• Connection behaviour
• Summary
Description of behaviour for design by moment-rotation characteristic

Connection exposed to bending

- Rotational stiffness
- Moment resistance
- Rotation capacity

Joint resistance $M_{j,Rd}$

Initial stiffness $S_{j,ini}$

Elastic limit $2/3 M_{j,Rd}$

Design curve

Experimental curve

M, moment, kNm

Rotation, $\phi$, mrad

Deformation capacity $\phi_{j,Cd}$

Joint resistance $M_{j,Rd}$

Initial stiffness $S_{j,ini}$

Elastic limit $2/3 M_{j,Rd}$

Design curve

Experimental curve

M, moment, kNm

Rotation, $\phi$, mrad

Deformation capacity $\phi_{j,Cd}$
Joint design

European standards

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**

\[ \phi = C_1(kM)^1 + C_3(kM)^3 + C_5(kM)^5 \]

- In EN1993-1-8 Ch.7 - Hollow section joints
Component model
Procedure

- Decomposition of joint
- Component description
- Joint assembly

Classification
Representation
Modelling in analyses

- Column web in tension
- Components in tension
- Components in compression
- Web panel in shear
- Column web in compression
- Joint
Component Model Application

- Design tables
  - Green book
  - Blue book

- Computer programs

- Simplified hand calculation
Component Model
Design tools

- Inputs
- Outputs
- Reports

For limited cases

www.fine.cz
Finite Element models of joint

- Research oriented
- Design oriented

Research model

Design model
Research oriented FEA
Current models of bolts

- Solid elements
- Complex models including
  - Tread
  - Tightening
- Material
  - damage model

Bearing
FEM modelling

- von-Mises yield criterion
- Damage models

Connections
FE research models

• Bursi and Jaspart (1998)
  – T-stub and Extended end-plate moment
  – LAGAMINE, a finite element research software
  – Used for further validation in COST C1 action
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

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

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
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
Component based FEM
System response quantity

- 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

Može P., Beg D., A complete study of bearing stress in single bolt connections, JCSR, 95 (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 of bolt

- Bars and springs
  - In tension – stiffness, resistance, deformation capacity
  - In shear – stiffness, resistance, deformation capacity
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

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Behaviour based on bolt failure
Validation for rupture of thread

Deformation, mm

Force, kN

Experiment

Research FEM

Introduction

Connection design

Models

Component method

FE analyse

Validation and verification

Component based

FEM

Bolted joints

Slender plates

Connection behaviour

Summary
Validation for tearing down of nut

![Graph showing force vs. deformation for experiment and research FEM]

- **Introduction**
- **Connection design**
  - Models
  - Component method
  - FE analyse
- **Validation and verification**
- **Component based FEM**
  - Bolted joints
  - Slender plates
- **Connection behaviour**
- **Summary**
Design model of bolt in tension

- Force-displacement diagram

![Diagram of force-displacement relationship](image)

- Force in anchor bolt, kN
- Deformation, mm

Symbols:
- $F_{t,Rd}$
- $F_{t,el}$
- $F_{c,Ed}$
- $k$
- $U_{el}$
- $U_{t,Rd}$
Modelling of T stub behaviour

- Research model
  - Validation
- Design model
  - Verification
T stub behaviour
Research FE model

- MIDAS FEM
- Mesh sensitivity study
Experiment with T stub

HEB300  HEB400

Connection design
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FEM
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Connection behaviour

Summary
Validation – global deformation

![Graph showing force vs. deformation for different materials](image)

- **Experiment**
- **Solid elements bolts**

**HEB300**

**Introduction**
- Connection design
  - Models
  - Component method
  - FE analyse

**Validation and verification**
- Component based
  - FEM
  - Bolted joints
  - Slender plates

**Connection behaviour**

**Summary**
Validation – local deformation

Plate deformation in yield line

- Experiment, strain gauge 11
- Research FEM
T stub design model
Verification

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

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

\[
F_{t,3,Rd} = 2F_{t,Rd}
\]

CBFEM:
Yielding of flange

Bolt resistance
T stub design model
Verification

- Component method
- CBFEM
- Research FEM

Resistance [kN] vs. Flange thickness [mm]
T stub design model
Verification

Variation of
- Plate thickness
- Bolt size
- Bolt material
- Bolt distance
- T stub thickness

Resistance CB FEM [kN]
Resistance - Component method [kN]
Design model
Slender plate in compression

- Column web
- Stiffeners

![Diagram showing different connection designs](#)
Research FEM

- Shell elements, true-stress true strain material model, mesh sensitivity
- Geometrical and material nonlinear model with imperfections (GMNIA)
- Imperfections based on 1\textsuperscript{st} 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 $b_f$
Stiffener with free edge

\[ h = w = 400 \text{ mm}, \ t = 4 \text{ mm} \text{ and } t = 6 \text{ mm} \]
Stiffener with partial stiffened edge

\[ h = w = 400 \text{ mm}, \ t = 6 \text{ mm}, \ t_f = 6 \text{ mm}, \ b_f = 60 \text{ mm} \]
Stiffener with partial stiffened edge

h = w = 400 mm, t = 4 mm, tf = 12 mm, bf = 120 mm
Validation of research model
Free edge

![Graph showing force vs. deformation]

- **Force** [kN] vs. **Deformation** [mm]
- **EXP** - Horizontal deformation
- **EXP** - Vertical deformation
- **RFEM** - Horizontal deformation
- **RFEM** - Vertical deformation

**Deformation**

![Deformation visualizations with von Mises stress]

- **σ von Mises**
Design model
Slender plate in compression

- Buckling analysis

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<td>6</td>
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</table>

Reduced stress method

- According to EN 1993-1-5 Annex B
- Critical buckling factor - Linear buckling analyses $\alpha_{cr}$
- Load amplifier - Material nonlinear analyses $\alpha_{ult,k}$
- Plate slenderness $\bar{\lambda}_p = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr}}}$
- Plate buckling reduction factor $\rho$
- Evaluation $\frac{\rho \cdot \alpha_{ult,k}}{\gamma M_1} \geq 1$
Connection behaviour
bolted connections of open section

• Generally
  – Shear
  – Tension
  – Compression

• Research model
  – Validation

• Design model
  – Verification
Generally loaded connections

Experiments – beam splices
Generaly loaded connections verification and validation

- **Experiments**
- **Component method – linear interaction**
- **Component method – quadratic interaction**
- **CBFEM**

![Graph showing bending moments](image-url)

- Bending moment $M_z$ [kNm]
- Bending moment $M_y$ [kNm]

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Introduction

Connection design
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Validation and verification

Component based FEM
- Bolted joints
- Slender plates

Connection behaviour

Summary
Global behavior - sample 0°

- CBFEM - 0°
- Component method – 0°
- Experiment – sample 0°
Prediction of Deformation capacity

- Question of limiting strain
  - Accuracy in case small deformations
  - Moderated influence to resistance
  - For resistance $\varepsilon_{Cd} = 5\%$
  - For deformation capacity $\varepsilon_{Cd} = 15\%$

![Graph showing moment vs. rotation for different strain limits](image)
Prediction of Deformation capacity

Question of not guaranteed values of yield strength of the structural steel

- Actual yield strength - EN 1998-1-8 cl. 6.2

Overstrenght factor $\gamma_{ov} = 1.25$

$\sigma_{y,max} \leq 1.1 \gamma_{ov} f_y$

![Graph showing the relationship between moment and rotation for various yield strengths.](image)
Prediction of global and local behaviour

Beam to column connection

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

M = 180 kNm
Fi = 5.7 mrad
Si = 31.5 MNm/rad

Column web plastification
Global and local behaviour

M = 250 kNm
Fi = 10,7 mrad
Si = 23,4 MNm/rad

Column web full plastification

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Global and local behaviour

Further plastification

- $M = 280 \text{ kNm}$
- $F_i = 43,6 \text{ mrad}$
- $S_i = 6,4 \text{ MNm/rad}$
Global and local behaviour

Resistance reached - 5 % strain

M = 290 kNm
Fi = 78,6 mrad
Si = 3,7 MNm/rad
Global and local behaviour

To deformation capacity $\varepsilon_{Cd} = 15 \%$

For increase strength $\gamma_{ov} = 1,25$

$1,25 \ f_y$
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

• **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
What are the predictive capabilities of our computer simulations?

„Essentially, all models are wrong, but some are useful”

Background references
Component based FEM


Thank you for your attention

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

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