TAMPERE UNIVERSITY OF TECHNOLOGY

Unified approach for structural behavior of RHS T joints

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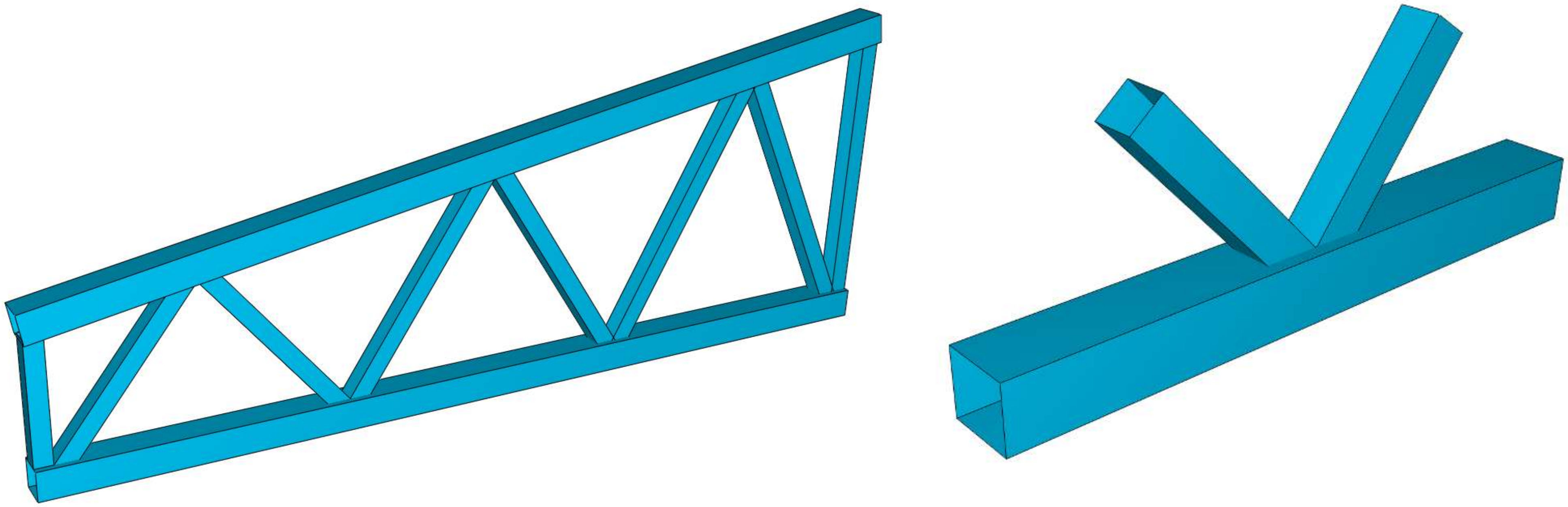
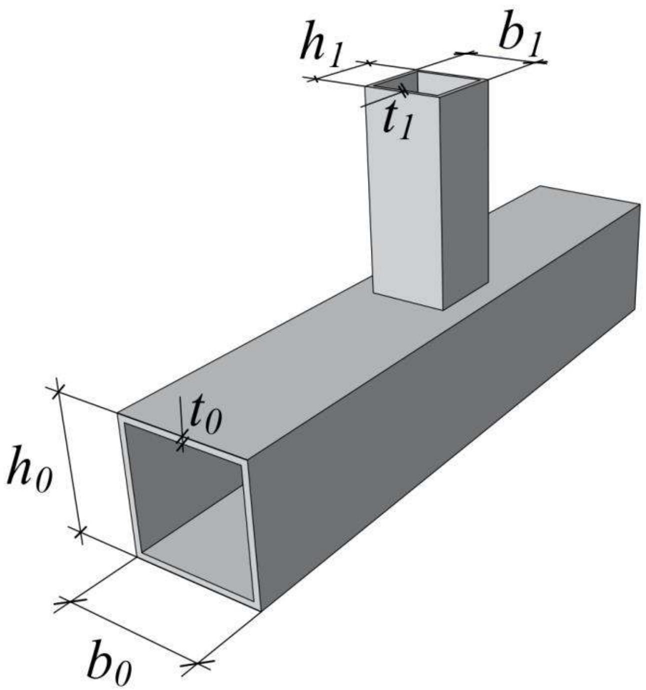


Goal: Cost optimization for tubular trusses with **semi-rigid joints**

Need: Unified approach for **design resistance** and **initial stiffness** of tubular joints under **arbitrary loading**

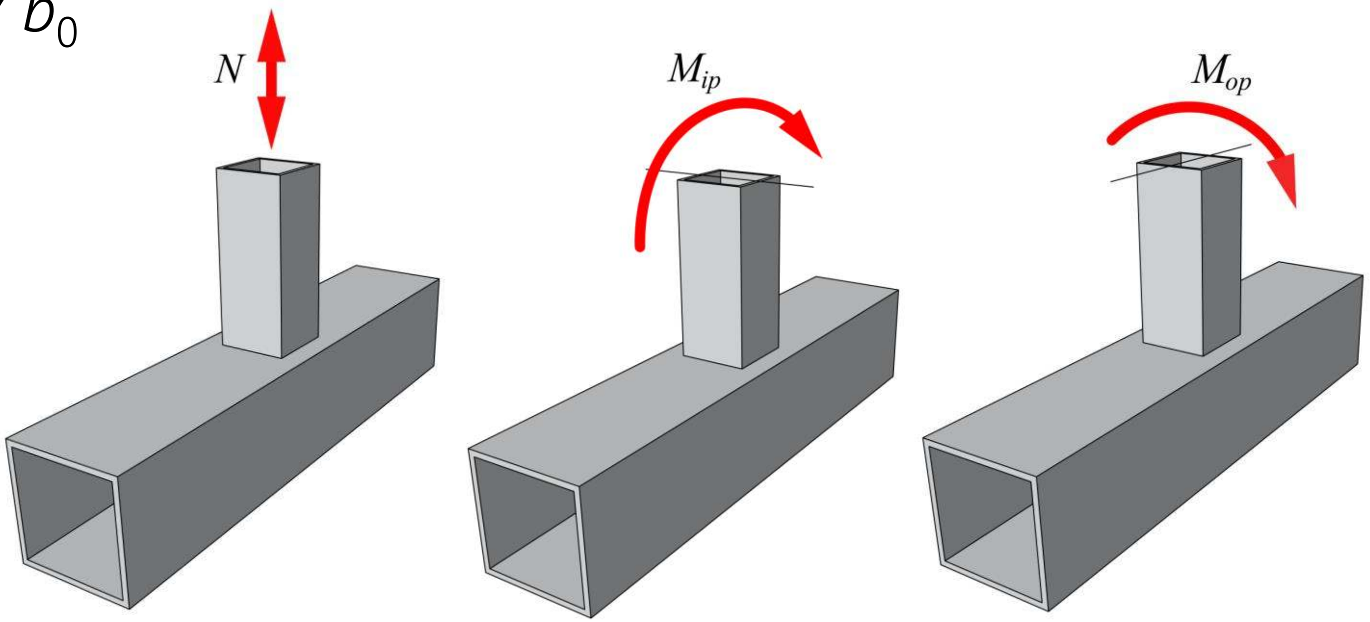


Notations

b_0, h_0, t_0	Chord dimensions
b_1, h_1, t_1	Brace dimensions
f_{y0}, f_{u0}	Chord material properties
a	Fillet weld size
$\beta = b_1 / b_0$	
$\eta = h_1 / b_0$	

Loading

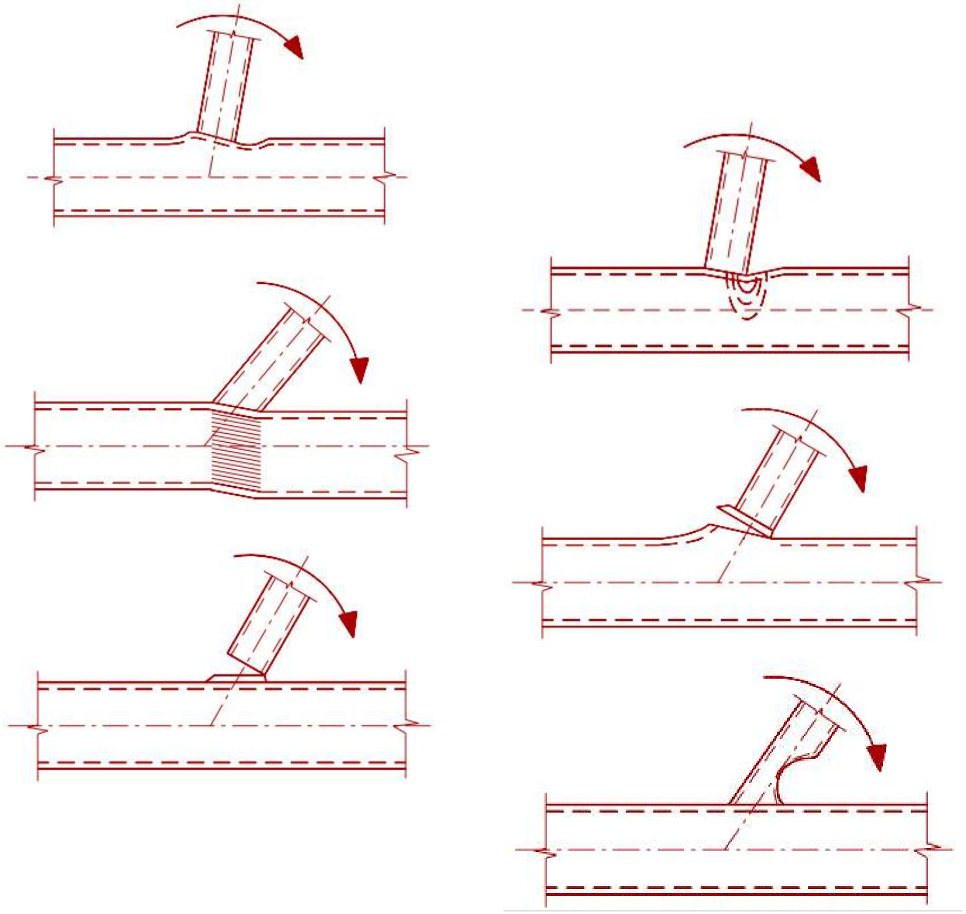
- axial force N
- in-plane moment M_{ip}
- out-of-plane moment M_{op}



EN 1993-1-8:2005 - **Failure modes approach**

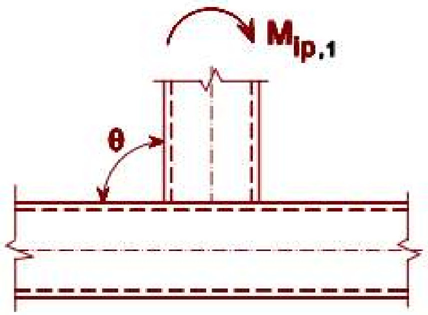
Possible failure modes:

- Chord face failure
- Chord side wall failure
- Chord shear failure
- Punching shear
- Brace failure
- Local buckling



EN 1993-1-8:2005 - **Failure modes approach**

1. Geometry of the joint
2. Limiting failure mode
3. Resistance by simple equations

T and X joints	Design resistance	
In-plane moments ($\theta = 90°$)	Chord face failure	$\beta \leq 0{,}85$
	$M_{ip,1,Rd} = k_n f_{y0} t_0^2 h_1 \left(\frac{1}{2\eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta} \right) / \gamma_{M5}$	
	Chord side wall crushing	$0{,}85 \leq \beta \leq 1{,}0$

EN 1993-1-8:2005 - **Failure modes approach**

- Simple & fast

Challenges

- Restricted by cases studied
- Additional checks for welds required
- **No rules for initial stiffness**

Possible solution

Component method

Brief history

1974, Zoetemeijer, bolted connections

1987, Tschemmernegg et al.

1995, Wald, column bases

1998, Grotmann & Sedlacek, rotational stiffness

2001, Weynand & Jaspart, hollow section joints

2008, da Silva, 3D joints

2009, Heinisuo et al., end plate joints

2015, Weynand et al., **general approach for all types of joints**

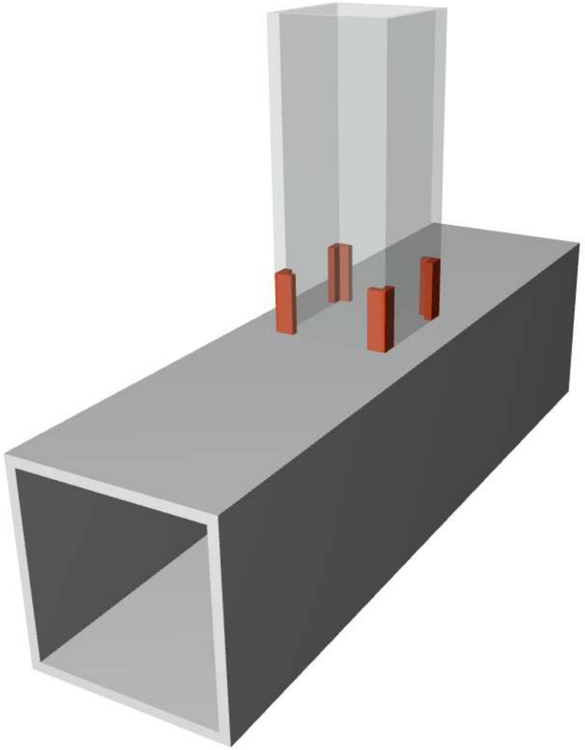
Currently: EN 1993-1-8 for joints connecting H or I sections

This research

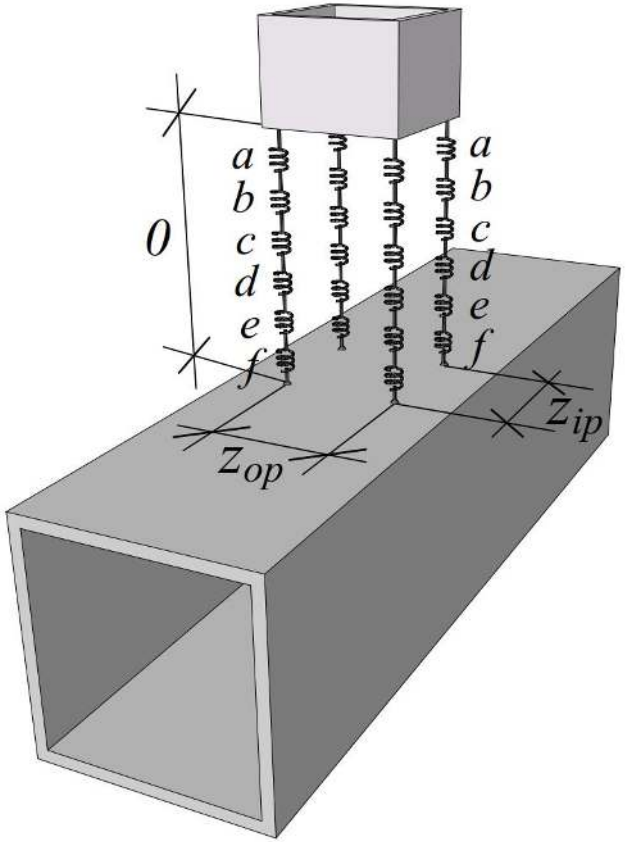
Component method for **RHS T joints** under arbitrary loading

Major concept

1. Load is transferred through loading zones



2. Component model



a) chord face in bending
b) chord side walls in tension or compression
c) chord side walls in shear
d) chord face under punching shear
e) brace flange or webs in tension or compression
f) welds

Major concept

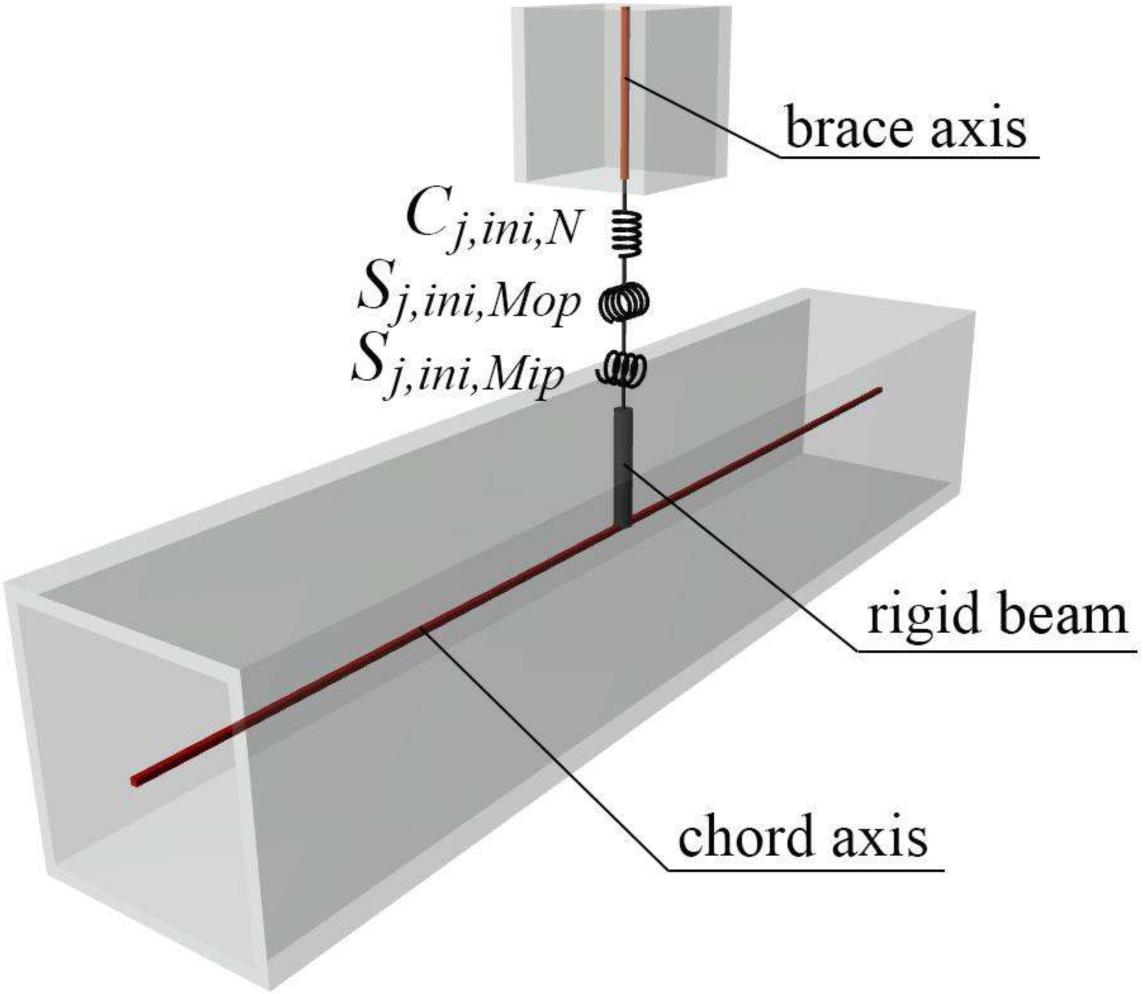
3. Active components
4. Resistance and stiffness of active components
5. Design resistances and initial stiffnesses of joint

Simplified design model

$C_{j,ini,N}$ axial longitudinal stiffness

$S_{j,ini,Mip}$ rotational in-plane stiffness

$S_{j,ini,Mop}$ rotational out-of-plane stiffness



1. Active components (Weynand et al., 2015)

	Component	Axial force			In-plane moment		Out-of-plane moment	
a	Chord face in bending	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$		$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$
		●	–		●	–	●	–
b	Chord side wall(s) in tension or compression	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$	$\beta = 1.0$	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$
		–	●	●	–	●	–	●
c	Chord side wall(s) in shear	–	–	–	–	–	–	–
d	Chord face under punching shear	$\beta \leq 0.85$	$0.85 < \beta \leq (1–1/\gamma)$	$\beta > (1–1/\gamma)$	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$
		–	●	–	–	–	–	–
e	Brace flange and web(s) in tension or compression	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$		$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$	$\beta \leq 0.85$	$0.85 < \beta \leq 1.0$
		–	●		–	●	–	●
f	Welds	●	●		●	●	●	●

2. Resistances of active components (Weynand et al., 2015)

$$F_{a,N,Rd}; F_{b,N,Rd}; F_{c,N,Rd}; F_{d,N,Rd}; F_{e,N,Rd}; F_{f,N,Rd}$$

$$F_{a,Mip,Rd}; F_{b,Mip,Rd}; F_{c,Mip,Rd}; F_{d,Mip,Rd}; F_{e,Mip,Rd}; F_{f,Mip,Rd}$$

$$F_{a,Mop,Rd}; F_{b,Mop,Rd}; F_{c,Mop,Rd}; F_{d,Mop,Rd}; F_{e,Mop,Rd}; F_{f,Mop,Rd}$$

3. Minimum resistances

$$F_{N,\min,Rd} = \min\left[F_{a,N,Rd}; F_{b,N,Rd}; F_{c,N,Rd}; F_{d,N,Rd}; F_{e,N,Rd}; F_{f,N,Rd}\right]$$

$$F_{Mip,\min,Rd} = \min\left[F_{a,Mip,Rd}; F_{b,Mip,Rd}; F_{c,Mip,Rd}; F_{d,Mip,Rd}; F_{e,Mip,Rd}; F_{f,Mip,Rd}\right]$$

$$F_{Mop,\min,Rd} = \min\left[F_{a,Mop,Rd}; F_{b,Mop,Rd}; F_{c,Mop,Rd}; F_{d,Mop,Rd}; F_{e,Mop,Rd}; F_{f,Mop,Rd}\right]$$

4. Design resistances of joint

$$N_{Rd} = 4 \cdot F_{N,\min,Rd}$$

$$M_{ip,Rd} = 2 \cdot F_{Mip,\min,Rd} \cdot z_{ip}$$

$$M_{op,Rd} = 2 \cdot F_{Mop,\min,Rd} \cdot z_{op}$$

5. Final resistance

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

1. Component ***a*** (chord face in bending)

$$k_a = \frac{t_0^3}{14.4\beta L_{stiff}^2}\left(\frac{L_{stiff}^2}{bt_0}\right)^{1.25} \frac{\frac{c}{L_{stiff}} + \left(1 - \frac{b}{L_{stiff}}\right)\tan\theta}{\left(1 - \frac{b}{L_{stiff}}\right)^3 + \frac{10.4\left(1.5 - 1.6\frac{b}{L_{stiff}}\right)}{\left(\frac{L_{stiff}}{t_0}\right)^2}}$$

(Weynand et al., 2015)

$$k_a = \frac{20 \cdot t_0^3 \cdot l_{eff,cf}}{(1-\beta)^3 \cdot b_0^3} \cdot \frac{1}{2 + \frac{6\beta}{1-\beta}}$$

(Grotmann & Sedlacek, 1998)

2. Component ***b*** (chord side wall in tension or compression)

$$k_b = \frac{2 \cdot b_{eff,c,wc} \cdot t_0}{h_0}$$

(Weynand et al., 2015)

$$k_b = \frac{2 \cdot t_0 \cdot b_{eff,cw,el}}{h_0 - 3t_0}$$

(Grotmann & Sedlacek, 1998)

3. Component ***c*** chord side wall in shear)

$$k_c = 0.38 \cdot \frac{A_{VC}}{\beta z_{ip}}$$

(Weynand et al., 2015)

4. Component ***d*** (chord face under punching shear)

$$k_d = \infty$$ (Weynand et al., 2015)

5. Component ***e*** **(**brace flange and web in tension or compression)

$$k_e = \infty$$ (Weynand et al., 2015)

6. Component ***f*** **(**welds)

$$k_f = \infty$$ (Weynand et al., 2015)

Longitudinal stiffness

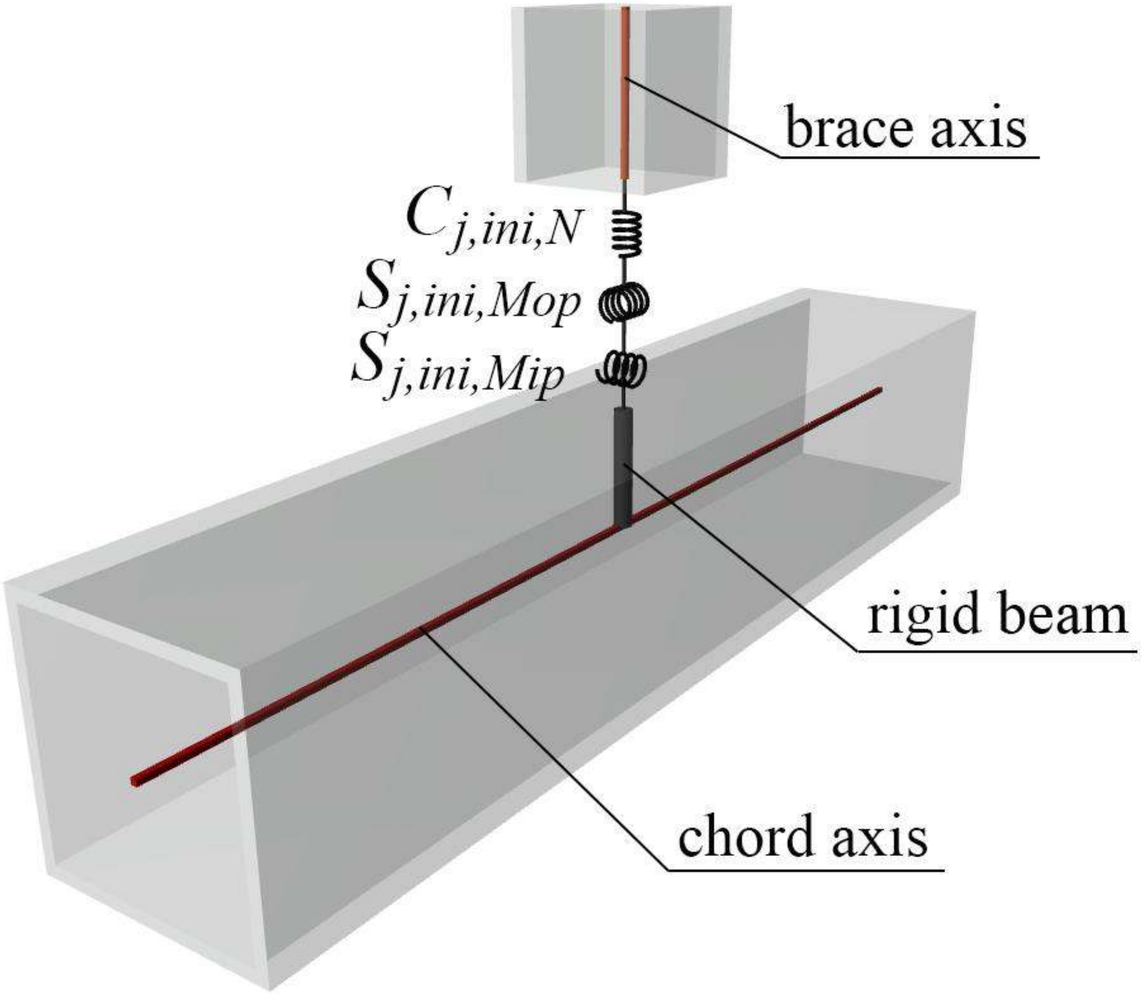
$$C_{j,ini,N} = \frac{Ek_{sn,N}}{\frac{1}{k_a} + \frac{2}{k_b}}$$

Rotational in-plane stiffness

$$S_{j,ini,ip} = \frac{Eh_1^2 k_{sn,ip}}{\frac{2}{k_a} + \frac{2}{k_b} + \frac{1}{k_c}}$$

Rotational out-of-plane stiffness

$$S_{j,ini,op} = \frac{Eb_1^2 k_{sn,op}}{\frac{2}{k_a} + \frac{2}{k_b}}$$



In-plane bending

b_0 [mm]	150.6
h_0 [mm]	151.6
t_0 [mm]	7.98
f_{y0} [N/mm²]	478
f_{u0} [N/mm²]	537
E [GPa]	185
b_1 [mm]	100.33
h_1 [mm]	100.85
t_1 [mm]	7.94
Full penetration butt welds	

Experimental resistance:

$$M_{ip,\exp} = 18.5\ kNm;$$

Numerical resistance:

$$M_{ip,FEM} = 15.7\ kNm.$$

EN 1993-1-8:2005

$\beta = 0.67 < 0.85;$

Failure mode: *Chord face failure;*

Reduction factor: 0.9;

Design resistance:

$$M_{ip,1,Rd} = 17.2\ kNm.$$

Component method

$\beta = 0.67 < 0.85;$

Active components: *a*, *f*;

Reduction factor 0.9 for component *a*;

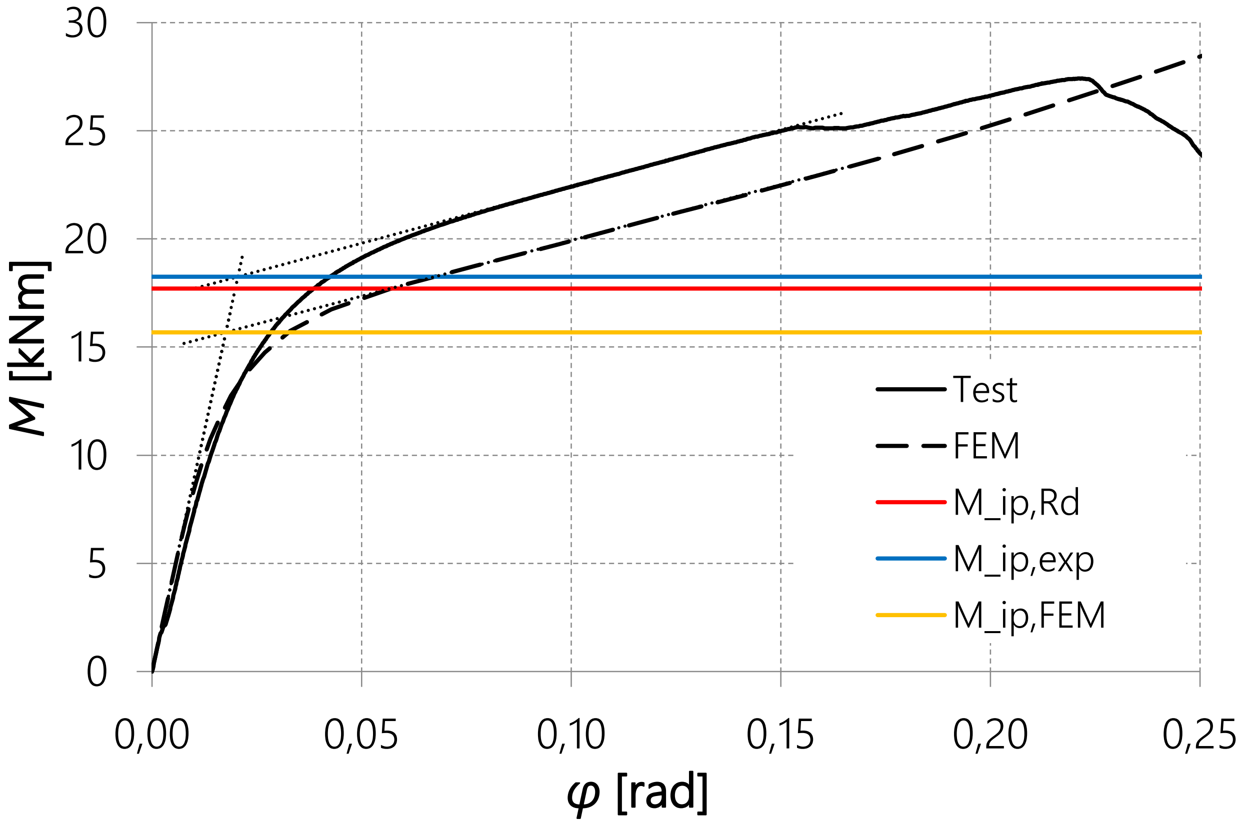
Resistances of the components:

$$F_{a,Mip,Rd} = 92.4\ kN;\ F_{f,Mip,Rd} = 171.1\ kN;$$

Design resistance:

$$M_{ip,Rd} = 17.2\ kNm.$$

In-plane bending



Initial rotational stiffness

Active components: *a*, *b*, *c*;

Stiffnesses of the components:

$k_a = 1.04\,mm;\ k_b = 8.61\,mm;\ k_c = 8.64\,mm;$

Design rotational stiffness:

$S_{j,ini,ip} = 830\ kNm/rad;$

Experimental rotational stiffness:

$S_{j,ini,ip,\exp} = 977\ kNm/rad;$

Numerical rotational stiffness:

$S_{j,ini,ip,FEM} = 888\ kNm/rad.$

Out-of-plane bending

b_0 [mm]	150.6
h_0 [mm]	151.6
t_0 [mm]	7.98
f_{y0} [N/mm^2]	478
f_{u0} [N/mm^2]	537
E [GPa]	185
b_1 [mm]	100.33
h_1 [mm]	100.85
t_1 [mm]	7.94
Full penetration butt welds	

EN 1993-1-8:2005

$\beta = 0.67 < 0.85;$

Failure mode: *Chord face failure;*

Reduction factor: 0.9;

Design resistance:

$M_{op,1,Rd} = 17.5\ kNm.$

Component method

$\beta = 0.67 < 0.85;$

Active components: *a*, *f*;

Reduction factor 0.9 for component *a*;

Resistances of the components:

$F_{a,Mip,Rd} = 92.9\ kN;\ F_{f,Mip,Rd} = 172.0\ kN;$

Design resistance:

$M_{op,1,Rd} = 17.5\ kNm.$

Axial loading

b_0 [mm]	140
h_0 [mm]	80
t_0 [mm]	4
f_{y0} [N/mm²]	361.9
f_{u0} [N/mm²]	418.6
E [GPa]	200
b_1 [mm]	100
h_1 [mm]	100
t_1 [mm]a	3
a [mm]	5

Experimental resistance:

$$N_{\exp} = 84.5\,kN;$$

Numerical resistance:

$$N_{FEM} = 90.0\,kN.$$

EN 1993-1-8:2005

$$\beta = 0.71 < 0.85;$$

Failure mode: *Chord face failure;*

Design resistance without chord stress function:

$$N^*_{1,Rd} = 72.3\,kN;$$

Chord stress function:

$$k_n = 0.87;$$

Design resistance:

$$N_{1,Rd} = 62.8\,kN.$$

Component method

$$\beta = 0.71 < 0.85;$$

Active components: *a*, *f*;

Resistances of the components without chord stress function:

$$F^*_{a,N,Rd} = 18.1\,kN;\ F_{f,N,Rd} = 144.6\,kN;$$

Chord stress function:

$$k_n = 0.87;$$

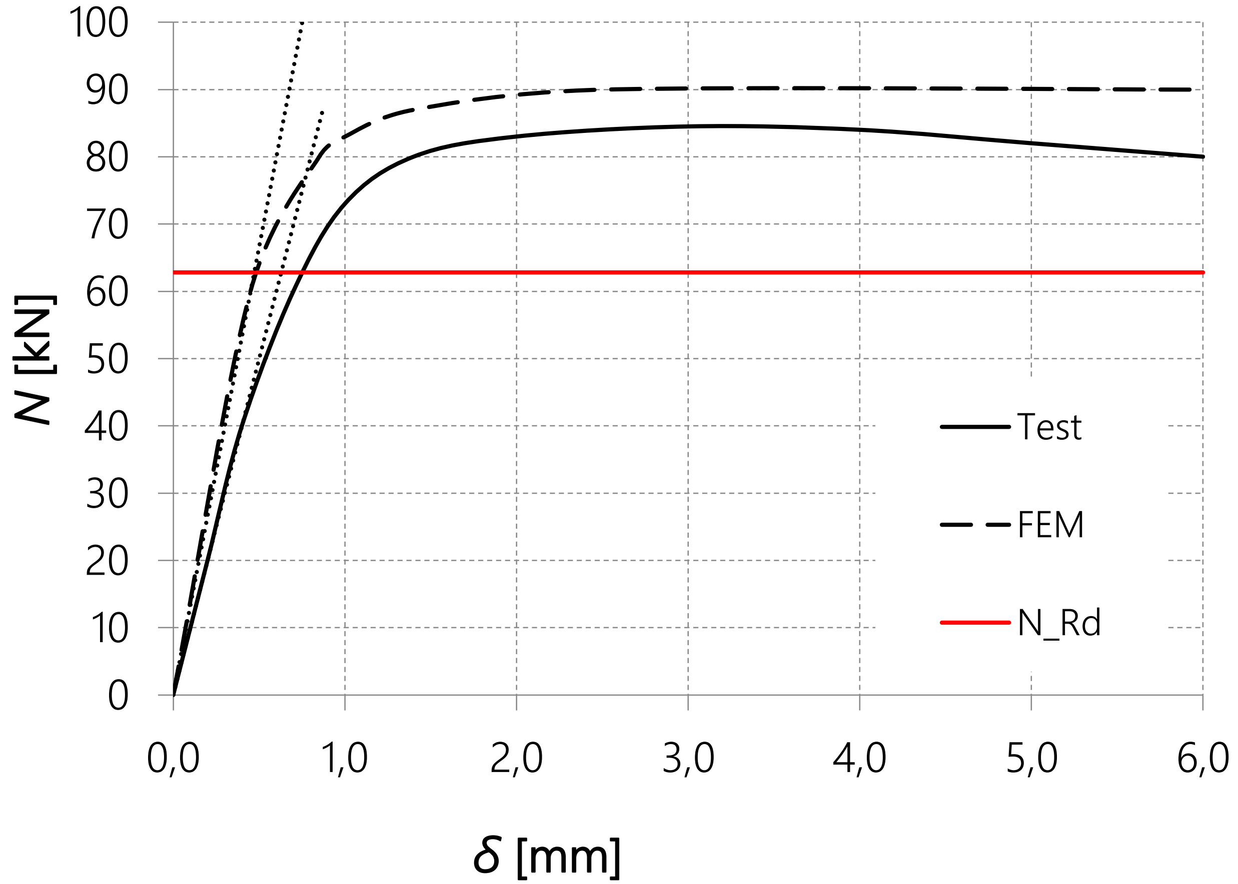
Resistances of the components:

$$F_{a,N,Rd} = 15.7\,kN;\ F_{f,N,Rd} = 144.6\,kN;$$

Design resistance:

$$N_{Rd} = 62.8\,kN;$$

Axial loading



Initial longitudinal stiffness

Active components: *a*, *b*;

Stiffnesses of the components:

$k_a = 1.91\, mm;\ k_b = 3.71\, mm;$

Design rotational stiffness:

$C_{j,ini,N} = 189\ kN / mm;$

Experimental rotational stiffness:

$C_{j,ini,N,\exp} = 100\ kN / mm;$

Numerical rotational stiffness:

$C_{j,ini,N,FEM} = 133\, kN / mm.$

Discussions

1. Eurocode-based approach of component method -> **safe design resistances**
2. Larger amount of calculations
3. Unclear axial and in-plane stiffnesses, **uncovered out-of-plane stiffness**
4. Joints assumed to behave similarly in compressions and tension

Further investigations

1. Parametric studies for verification
2. Chord stress functions for stiffness
3. Interaction of loads
4. Reduction coefficients for HSS
5. Effect of fillet welds