TAMPERE UNIVERSITY OF TECHNOLOGY

Initial rotational stiffness of tubular joints with axial force at main girder

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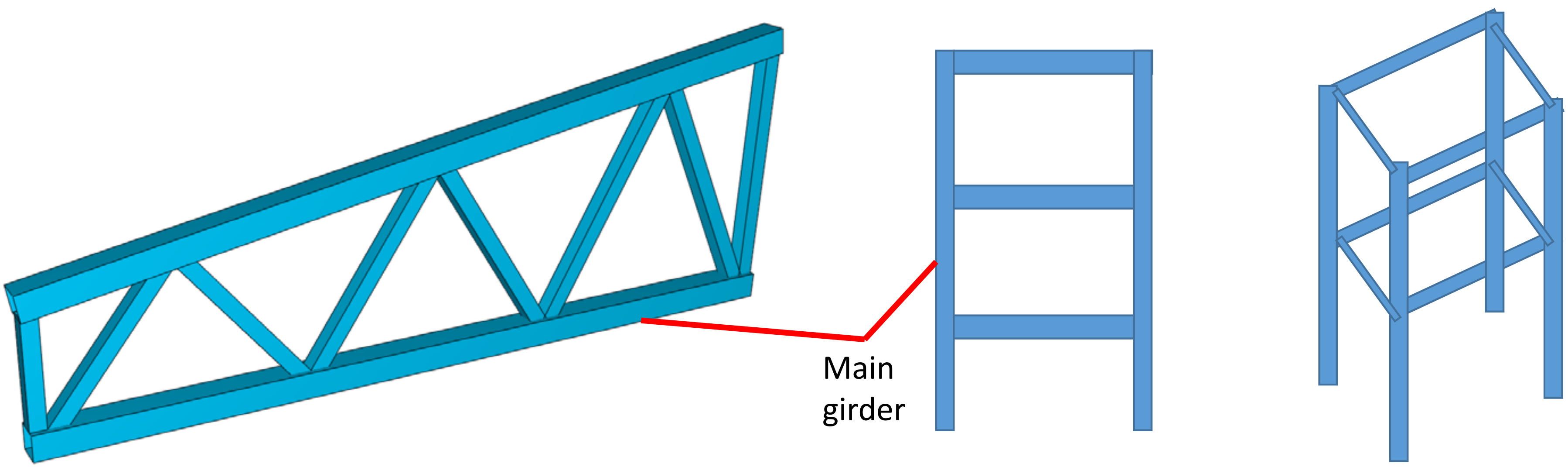
Journal of Structural Mechanics 50 years anniversary seminar
24-25 August 2017, Vaasa, Finland

Goal

Cost optimization of welded tubular HSS frames with **semi-rigid joints**

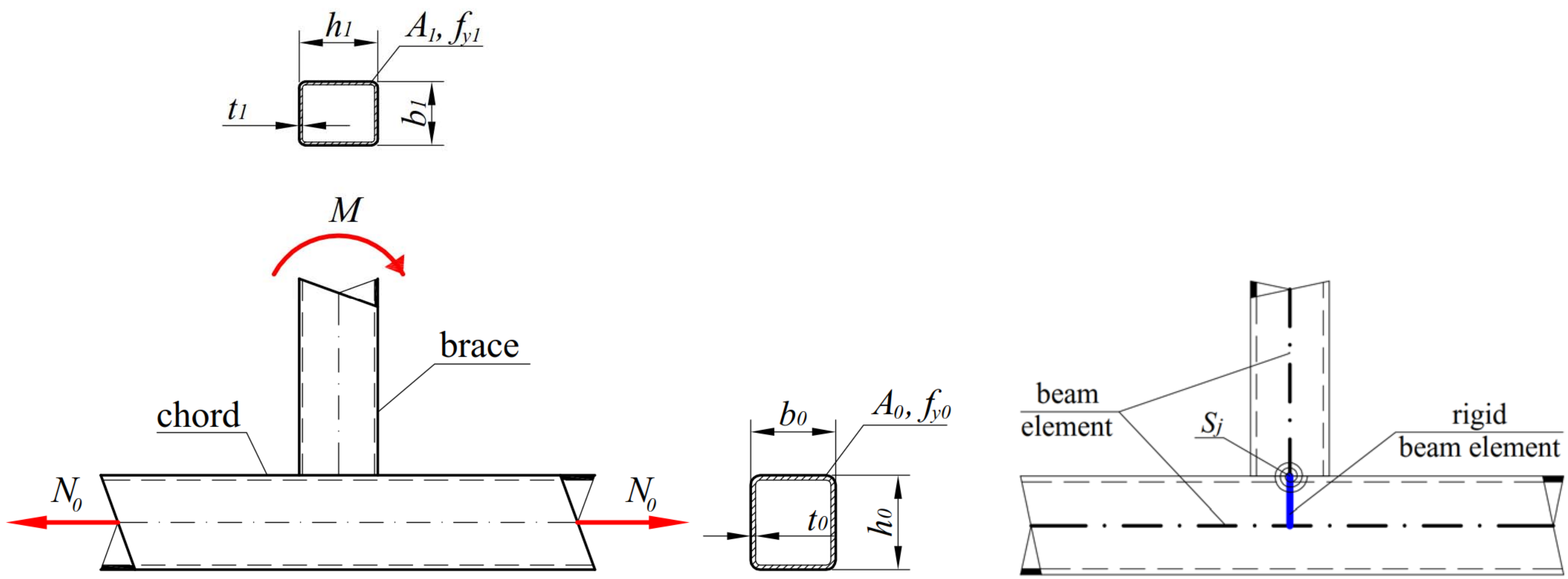
Need

Initial stiffness of rectangular hollow section joints under **in-plane moment**



Current research

The simplest configuration: T joint

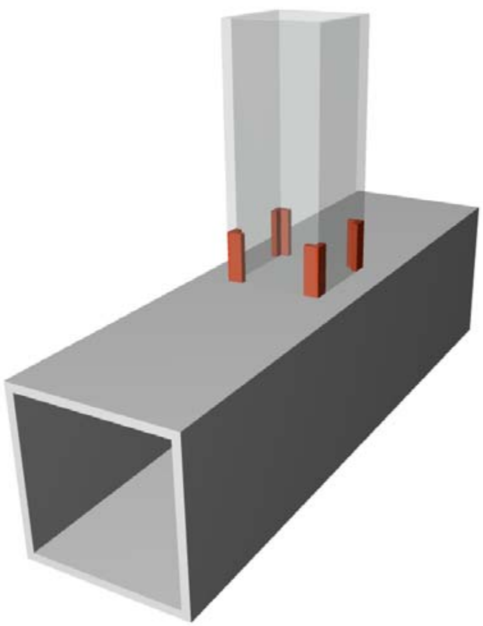


Theoretical approach: component method

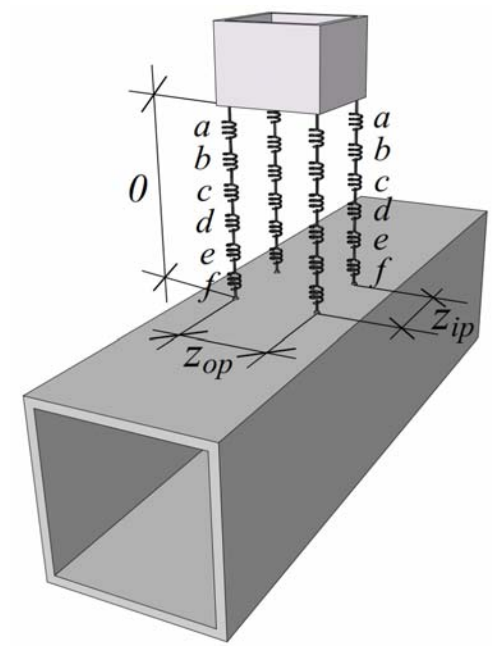
- EN 1993-1-8:2005 “Design of joints”. Only CHS joints, no rules for RHS joints
- CIDECT report 5BB – 8/98 (Grotmann&Sedlacek, 1998). Initial rotational stiffness for RHS T joints
- CIDECT report 16F – 3/15 (Weynand et al., 2015). Initial rotational stiffness for any type of joints, including RHS. Currently is being developed

Component method. 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

Component method. Major concept

3. Active components

   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

Contribute to initial stiffness (a–c)

Ignored (assumed infinitely stiff) (d–f)

4. In-plane initial rotational stiffness

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

Experimental tests

- HAMK/TUT (Finland)
- TU Karlsruhe (Germany)
- Kobe University (Japan)
- University of Thrace (Greece)

FEM

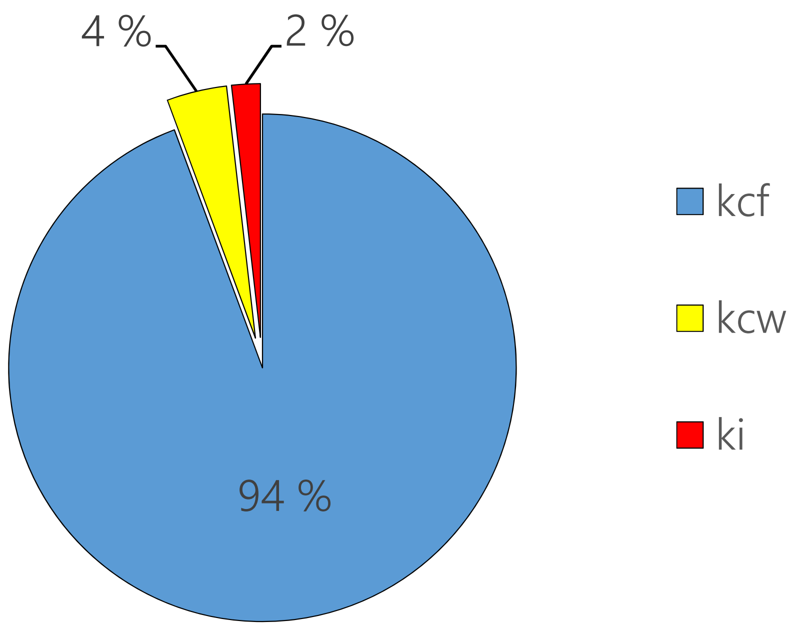
- TUT (Finland)

Problem

Theoretical approach considerably **underestimates** initial rotational stiffness.

Theoretical values account for **30-45% from** experimental / FEM values

Contributions of components



Underestimation is caused by **component *a* (chord face in bending)**

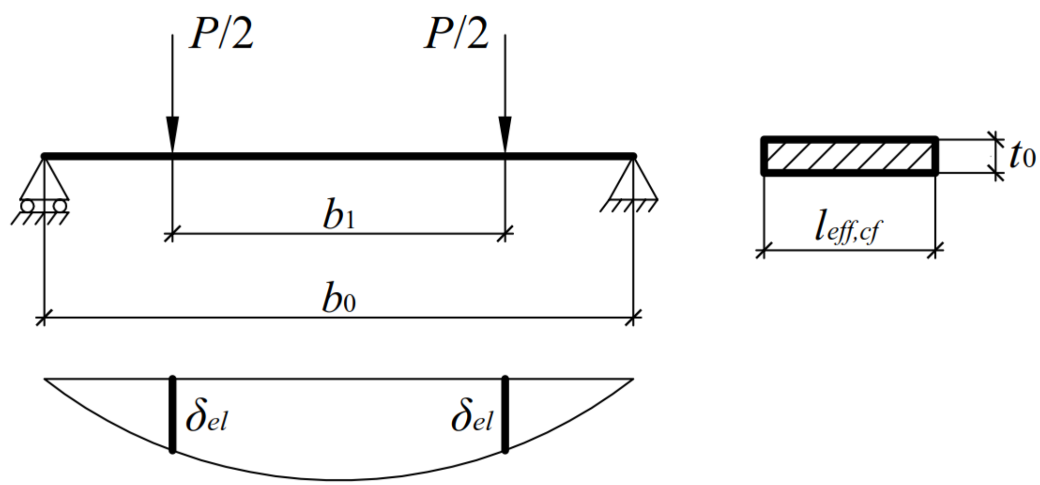
Component *a* (chord face in bending)

$$\delta_{el} = \frac{P}{48EI} \cdot (b_0 - b_1)^2 \cdot (b_0 + 2b_1)$$

$$I = \frac{t_0^3 \cdot l_{eff,cf}}{12}$$

$$\delta_{el} = \frac{P}{4Et_0^3 l_{eff,cf}} \cdot (b_0 - b_1)^2 \cdot (b_0 + 2b_1)$$

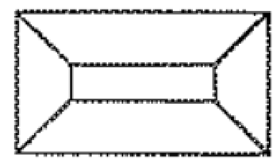
$$k_{cf} = \frac{P}{E\delta_{el}} = \frac{8t_0^3 l_{eff,cf}}{(1-\beta)^3 b_0^3} \cdot \frac{1}{2 + \frac{6\beta}{1-\beta}}$$



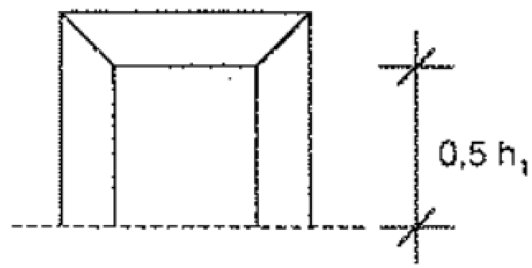
Effective length ($l_{eff,cf}$)

Length of the total yield line pattern for the perpendicular line load at the surface of the chord

- $l_{eff,cf} = t_1 + 2 \cdot b_0 \sqrt{1-\beta}$



- $l_{eff,cf} = \frac{h_1}{2} + b_0 \cdot \sqrt{1-\beta}$



Improved equation for component *a* (chord face in bending)

Based on comparison with experimental data

$$k_{cf} = \frac{\mathbf{8} t_0^3 l_{eff,cf}}{(1-\beta)^3 b_0^3} \cdot \frac{1}{2 + \frac{6\beta}{1-\beta}} \quad \Rightarrow \quad k_{cf} = \frac{\mathbf{20} t_0^3 l_{eff,cf}}{(1-\beta)^3 b_0^3} \cdot \frac{1}{2 + \frac{6\beta}{1-\beta}}$$

Validation. HAMK tests

Specimen	Chord	Brace	a_w [mm]	$S_{j,ini}$ [kNm/rad] Theory, old	Theory, new	Test	Theory / Test Old		New	
1111	150x150x8	100x100x8	6	401	913	1115	0.36		0.82	
2111	150x150x8	100x100x8	6	422	956	1083	0.39		0.88	
2211	150x150x8	100x100x8	6	421	954	995	0.42		0.96	
3111	150x150x8	100x100x8	6	405	919	1082	0.37	**0.39**	0.85	**0.87**
3211	150x150x8	100x100x8	6	403	916	1108	0.36		0.83	
3214	150x150x8	100x100x8	6	403	916	1282	0.31		0.71	
3311	150x150x8	120x120x8	6	1030	2113	1990	0.52		1.06	
1121	150x150x8	100x100x8	10	407	924	1692	0.24		0.55	
2121	150x150x8	100x100x8	10	423	958	1701	0.25		0.56	
2221	150x150x8	100x100x8	10	424	959	1452	0.29		0.66	
3121	150x150x8	100x100x8	10	397	903	1521	0.26	**0.29**	0.59	**0.64**
3221	150x150x8	100x100x8	10	401	913	1705	0.24		0.54	
3224	150x150x8	100x100x8	10	399	908	1455	0.27		0.62	
3321	150x150x8	120x120x8	10	1048	2141	2268	0.46		0.94	
1131	150x150x8	100x100x8	butt	414	940	893	0.46		1.05	
2131	150x150x8	100x100x8	butt	424	960	977	0.43		0.98	
2231	150x150x8	100x100x8	butt	425	961	1003	0.42	**0.45**	0.96	**1.00**
3131	150x150x8	100x100x8	butt	401	911	971	0.41		0.94	
3231	150x150x8	100x100x8	butt	409	930	961	0.43		0.97	
3331	150x150x8	120x120x8	butt	1100	2222	1990	0.55		1.12	

Validation. TH Karlsruhe and Kobe University tests

Specimen	Chord	Brace	a_w [mm]	$S_{j,ini}$ [kNm/rad] Theory, old	Theory, new	Test	Theory / Test Old		New	
M44	160x160x4	100x100x3	3	41	100	130	0.31	**0.35**	0.77	**0.82**
M45	160x160x5	100x100x3	3	79	191	260	0.30		0.73	
S12	200x200x9	150x150x6	6	1043	2325	2000	0.52		1.16	
S23	250x250x6	175x175x6	6	226	550	875	0.26		0.63	

Validation. University of Thrace tests

Specimen	Chord	Brace	a_w [mm]	$S_{j,ini}$ [kNm/rad] Theory, old	Theory, new	Test	Theory / Test Old		New	
80c150t5	150x150x5	80x80x5	6	46	111	135	0.34	**0.41**	0.82	**0.94**
80c150t6	150x150x6	80x80x5	6	78	189	208	0.38		0.91	
80c150t8	150x150x8	80x80x5	6	183	430	407	0.45		1.06	
100c150t5	150x150x5	100x100x5	6	104	249	301	0.34		0.83	
100c150t6	150x150x6	100x100x5	6	177	417	494	0.36		0.84	
100c150t8	150x150x8	100x100x5	6	408	924	712	0.57		1.30	
120c150t5	150x150x5	120x120x5	6	279	634	741	0.38		0.86	
120c150t6	150x150x6	120x120x5	6	469	1028	1366	0.34		0.75	
120c150t8	150x150x8	120x120x5	6	1041	2119	1927	0.54		1.10	
80c150t5	150x150x5	80x80x5	6	46	111	135	0.34		0.82	

Conclusions on initial stiffness

1. Original CIDECT approach considerably underestimates initial rotational stiffness of RHS T joints. $S_{j,ini} / S_{j,ini,exp}$ = 0,30…0,45.
2. Major contribution (>90%) is made by component *a* (chord face in bending).
3. New equation is proposed for stiffness of component *a*. $S_{j,ini} / S_{j,ini,exp}$ = 0,65…0,95.
4. Compared to butt welds, fillet welds significantly affect initial stiffness. Joints with 6 mm fillet weld have 13% higher stiffness, joints with 10 mm fillet weld have 36% higher stiffness. The influence can be considered by a simple rule:

   $$b_{1,eq} = b_1 + 2\sqrt{2} a_w k_{fw}$$

   a_w is fillet weld size

   k_{fw} is correlation coefficient (0,6…0,7)

Influence of axial stresses at main girder on resistance

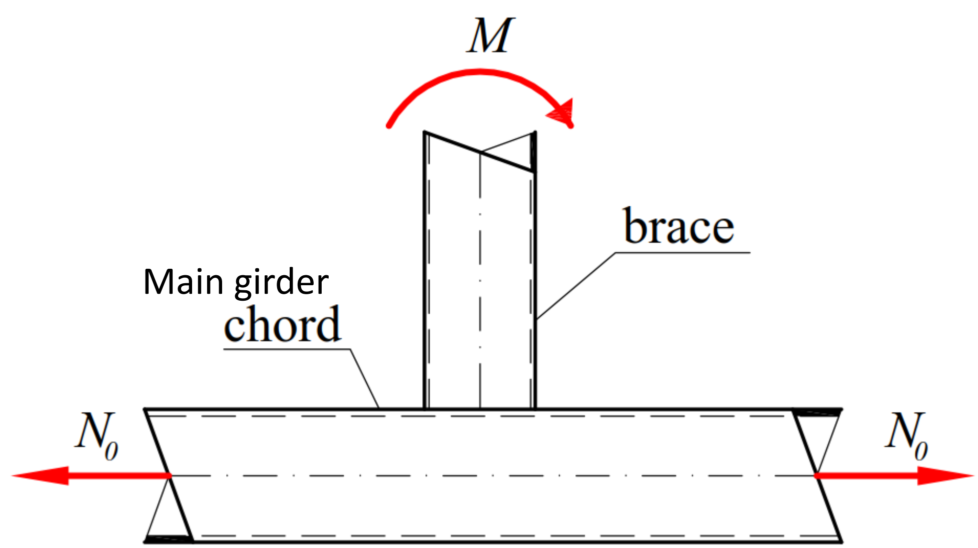
Axial stresses at the main girder reduce resistance of joints. This influence is considered by **chord stress function.**

$$M = \boldsymbol{k_n} f_{yo} t_0^2 h_1 \left(\frac{1}{2\eta} + \frac{2}{\sqrt{1-\beta}} + \frac{\eta}{1-\beta} \right)$$

k_n – chord stress function

$$k_n = \begin{cases} 1.3 - \dfrac{0.4|n|}{\beta} \leq 1.0, & n < 0 \\ 1.0, & n > 0 \end{cases}$$

$$n = \frac{\sigma_0}{f_{y0}} = \frac{N_0}{A_0 f_{y0}} + \frac{M_0}{W_{el0} f_{y0}} = \frac{N_0}{A_0 f_{y0}}$$



Influence of axial stresses in chord on initial stiffness

Influence of axial stresses in chord on initial stiffness is **not studied**

No chord stress function exists for initial stiffness

This study

Chord stress function for initial in-plane rotational stiffness, $\boldsymbol{k}_{sn,ip}$

Approach

1. FEM (Abaqus Standard)
2. Curve fitting (manual)

Scope of interest

Only square hollow section joints

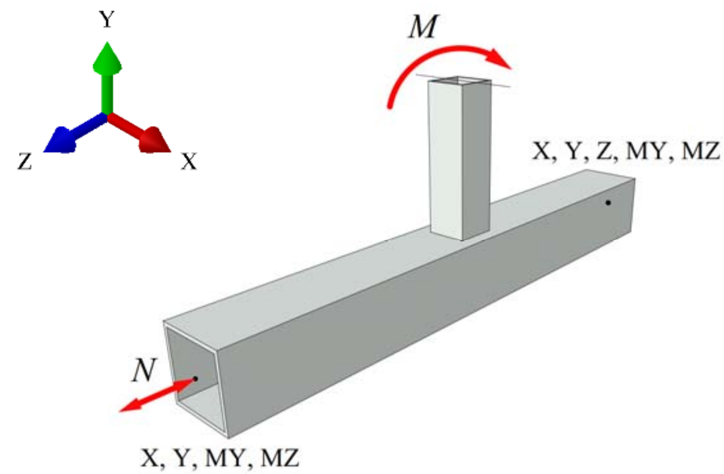
Chord		$300 \times 300 \times t_0$					
	t_0 [mm]	8.5	10	12	15	20	30
	2γ	35	30	25	20	15	10
Brace		$b_1 \times b_1 \times t_1$					
	b_1 [mm]	75	150	225	255	300	
	β	0.25	0.50	0.75	0.85	1.00	
n		-0.99, -0.95, -0.80, -0.60, -0.40, -0.20, 0, 0.20, 0.40, 0.60, 0.80, 0.95, 0.99					

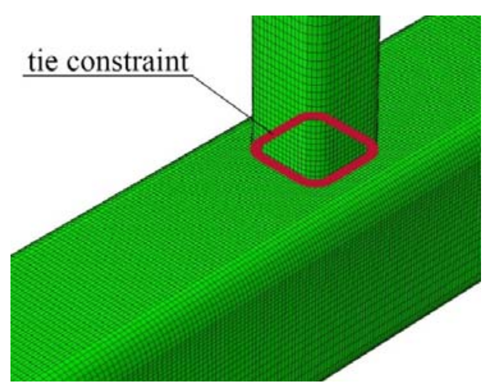
In total: 6x5x13=390 sample points

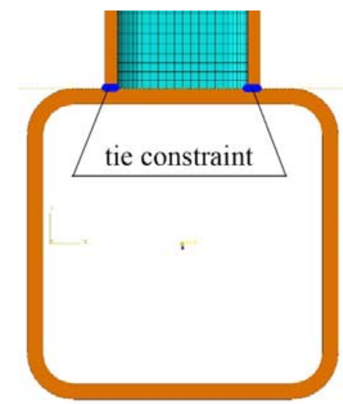
FEM analysis for every sample point

FEM

Chord length	$10b_0$
Brace length	$4b_1$
Mesh	20-noded brick with reduced integration (C3D20R), two elements in thickness direction
Welds	Butt welds (tie constraint)
Material	S500, ideal plastic, no hardening, same for chord and brace
Load	1. Axial load in chord 2. Concentrated moment at end of brace

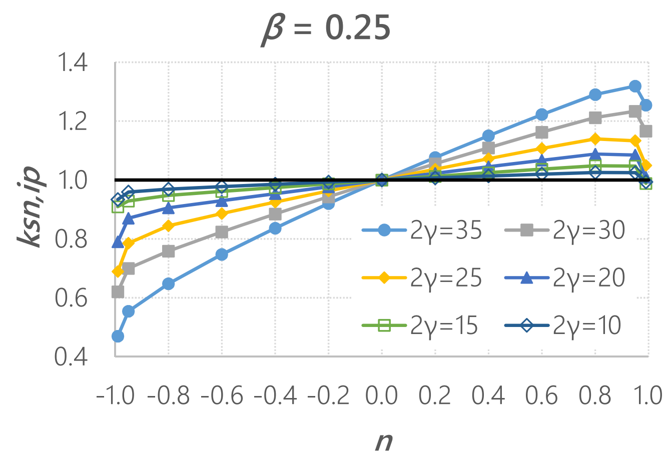


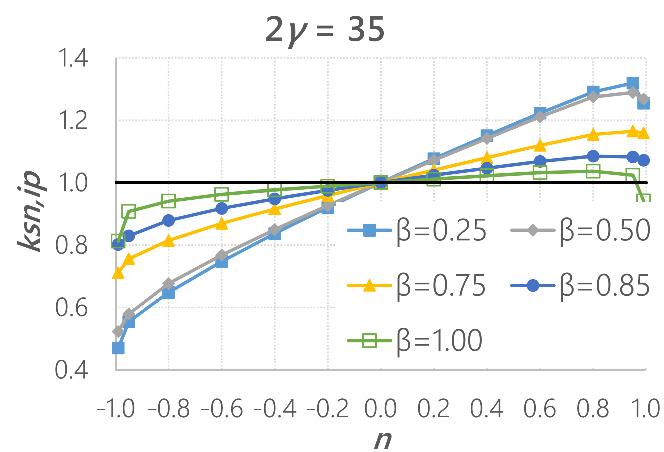




FEM observations

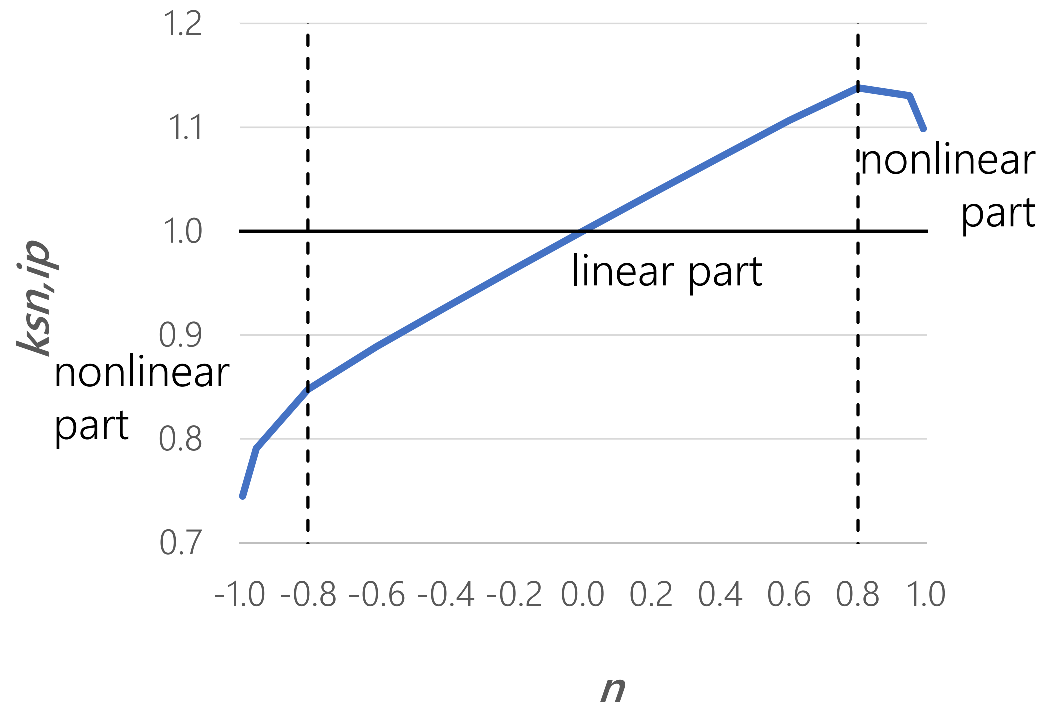
1. Reduction of stiffness for compressive loads, up to 50%
2. Increase of stiffness for tensile loads, up to 30%
3. Effect depends on β and γ. Effect weakens with large β and small γ
4. For $\beta = 1.0$, dependence on γ is negligibly small





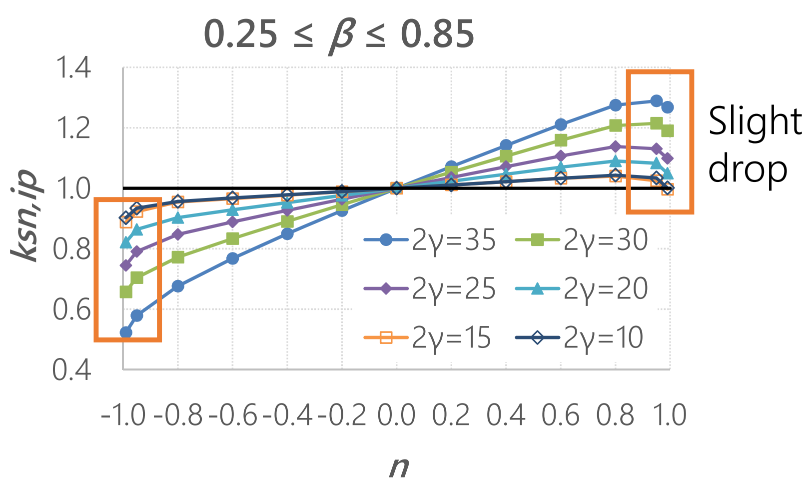
Curve fitting. Main principles

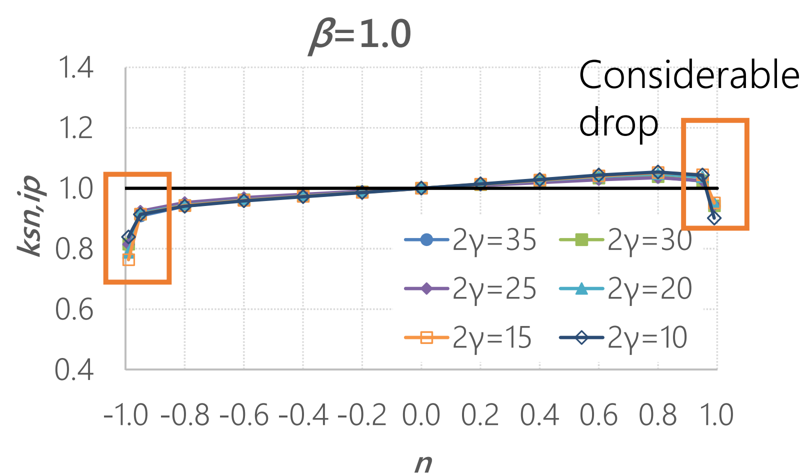
1. Three parts in *n*:
   - Nonlinear part, $-0.99 \leq n < -0.80$
   - Linear part, $-0.80 \leq n \leq 0.80$
   - Nonlinear part, $0.80 < n \leq 0.99$



Curve fitting. Main principles

2. Three parts in *β*:
   - 0.25 ≤ *β* ≤ 0.85 (dependent on *γ*, slight drop in nonlinear parts)
   - *β* = 1.0 (not dependent on *γ*, considerable drop in nonlinear parts)
   - 0.85 < *β* < 1.0 – linear interpolation





Curve fitting. Proposed equation

For $0.25 \le \beta \le 0.85$:

$$k_{sn,ip} = \begin{cases} 1 + 0.001 \cdot \left(1 + 1.7\beta - 2.6\beta^2\right) \cdot n \cdot \gamma^2 - 2.7 \cdot \left(|n| - 0.8\right)^2, & -0.99 \le n < -0.8 \\ 1 + 0.001 \cdot \left(1 + 1.7\beta - 2.6\beta^2\right) \cdot n \cdot \gamma^2, & -0.8 < n < 0.8 \\ 1 + 0.001 \cdot \left(1 + 1.7\beta - 2.6\beta^2\right) \cdot n \cdot \gamma^2 - 3.1 \cdot \left(n - 0.8\right)^2, & 0.8 < n \le 0.99 \end{cases}$$

For $0.85 < \beta < 1.0$:

$k_{sn,ip}$ is the linear interpolat ion between $\beta = 0.85$ and $\beta = 1.0$

For $\beta = 1.0$:

$$k_{sn,ip} = \begin{cases} 1 + 0.06 \cdot n - 3.5 \cdot \left(|n| - 0.8\right)^2, & -0.99 \le n < -0.8 \\ 1 + 0.06 \cdot n, & -0.8 < n < 0.8 \\ 1 + 0.06 \cdot n - 2.8 \cdot \left(n - 0.8\right)^2, & 0.8 < n \le 0.99 \end{cases}$$

Curve fitting. Validation

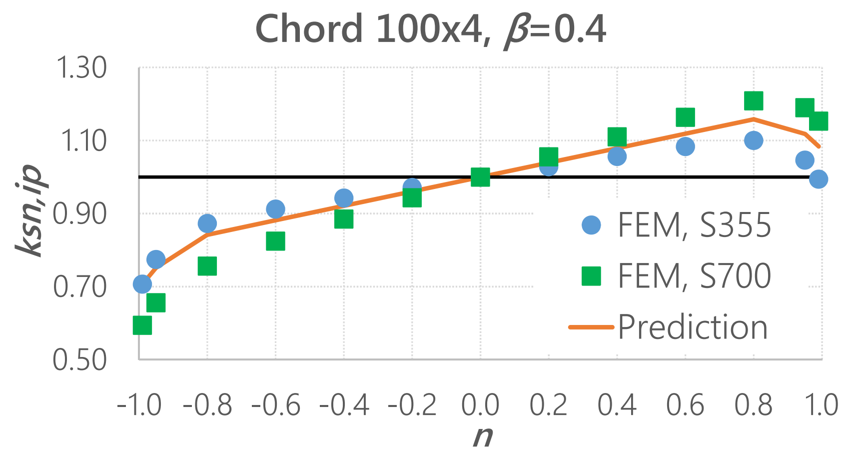
FEM for set of independent validation points

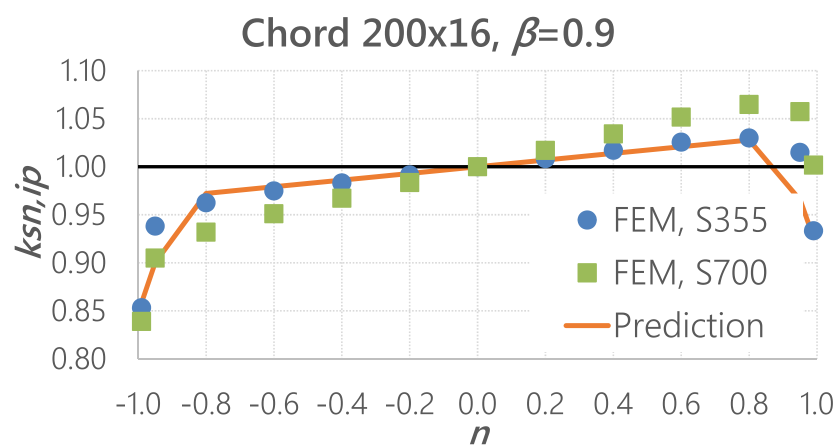
Chord	100 x 100 x t_0		200 x 200 x t_0	
t_0 [mm]	4	8	8	16
2γ	25	12.5	25	12.5
Brace	b_1 x b_1 x t_1		b_1 x b_1 x t_1	
b_1 [mm]	40	90	80	180
β	0.40	0.90	0.40	0.90
Steel grade	S355, S700			
n	-0.99, -0.95, -0.80, -0.60, -0.40, -0.20, 0, 0.20, 0.40, 0.60, 0.80, 0.95, 0.99			

In total: 4x2x2x13=208 independent validation points

Curve fitting. Validation

- Chord stress function is developed for S500, therefore, the effect is underestimated for S700 and overestimated for S355.
- Steel grade should be included in function
- Average error:
  2,0% for S355
  3,6% for S700
- Maximum error 19%





1. CIDECT approach for calculation initial rotational stiffness of RHS joints considerably underestimates experimental and numerical values. Improvement is proposed for stiffness of component "chord face in bending"
2. Axial stresses in chord significantly affect initial rotational stiffness of joints. Up to 50% reduction of stiffness for compressive loads, up to 30% increase of stiffness for tensile loads.
3. Chord stress function is proposed for initial rotational stiffness of square hollow section joints.
4. Steel grade should be included in chord stress function.
5. Function should be tested extended for RHS joints.


Tampere, 5-7 June 2018
ICCCBE 2018
17th International Conference on Computing in Civil and Building Engineering

Deadline for abstracts – September 15, 2017
Abstract notifications – November 1, 2017
Deadline for full papers – February 1, 2018
Full paper notifications – March 15, 2018
ICCCBE 2018 – June 5-7, 2018

KEYNOTE SPEAKERS

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