Analysis and design of cold-formed C-section members and structures

PhD Theses Open Discussion

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Introduction

- Basic research and industrial R&D
- Subject
  - compression C-section members
  - truss system made of C-section members
  - numerical modelling

Introduction

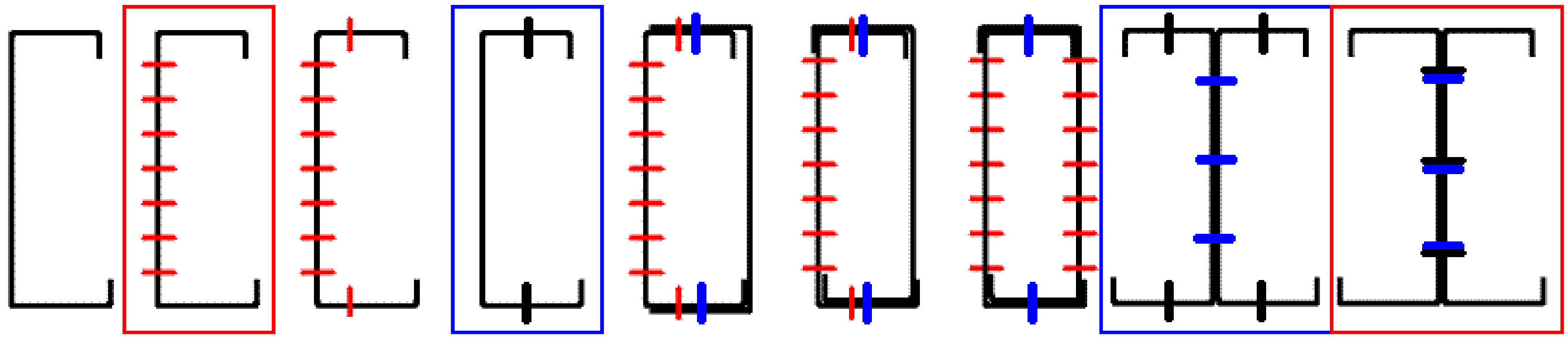
- General aims
  - stability behaviour
  - failure mode identification
  - load-bearing capacity
  - design method development
- Methodology
  - laboratory tests
  - standard-based calculations
  - numerical model development

C-section members

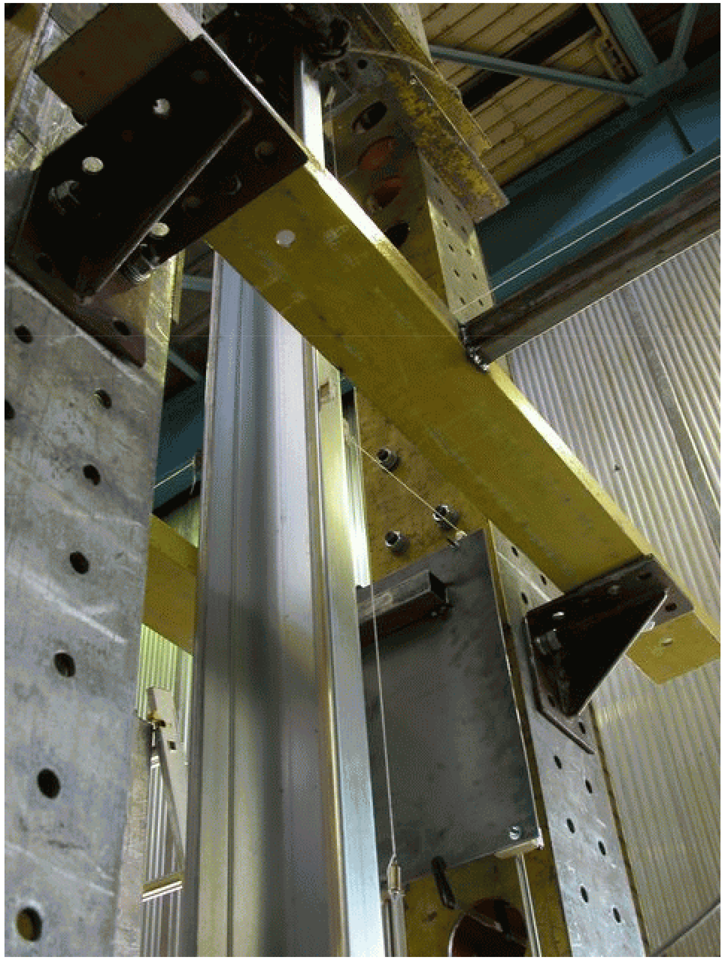
- Effect of load introduction
- Members with single and double sections
- 10 different arrangements
- C150/1.0 – C200/2.5
  - web b/t: 80-200
- Specimen lengths
  - 800, 1500, 2000, 2500, 3600 mm
- 37 + 61 tests (2002, 2008)

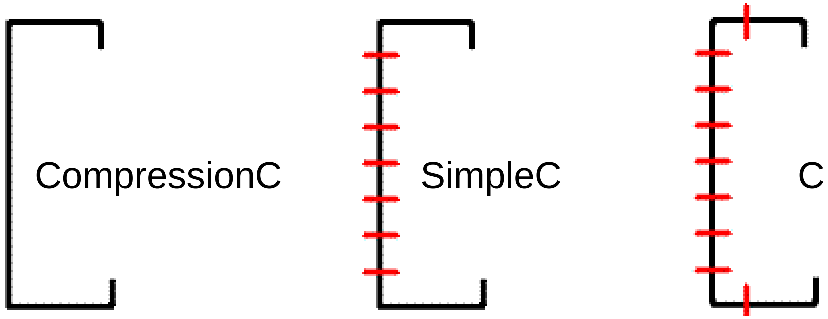
C-section members - specimens

- Single members with different eccentricities
- Doubled members – stuck into each-other
  - Two C-sections
  - C-section + U-section
- Doubled members – back-to-back arrangement
- Single member laterally supported by hat sections

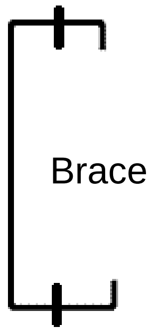


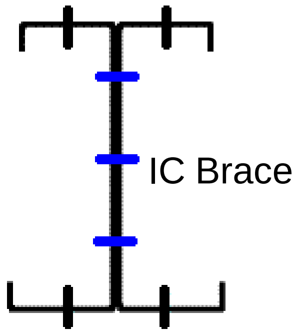
C-section members - tests

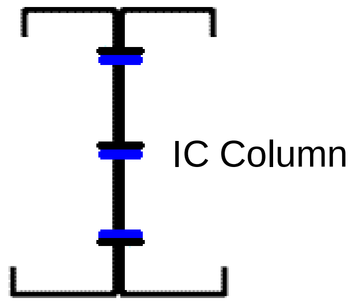


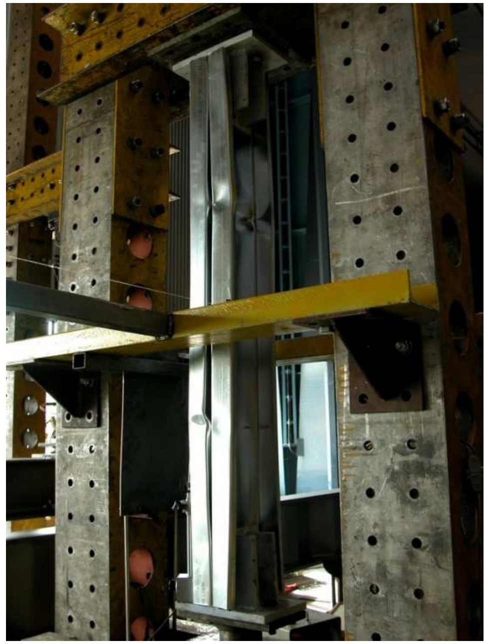


C-section members - tests

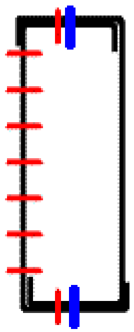




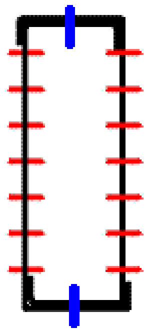




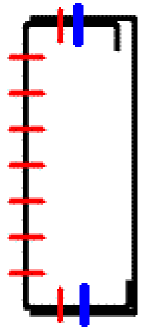
C-section members - tests



CC

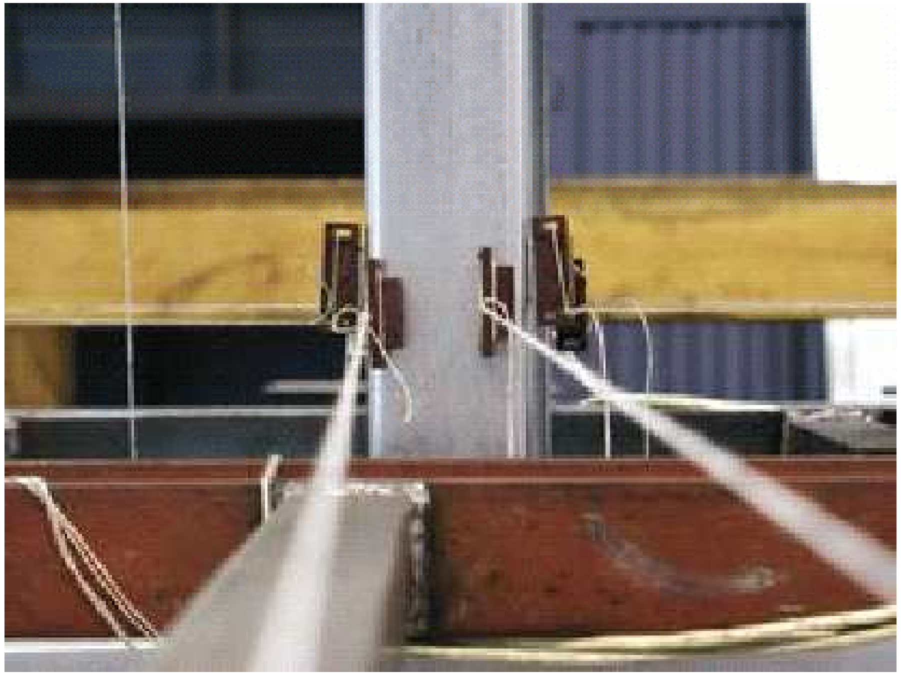


DoubleC



CU

C-section members - tests

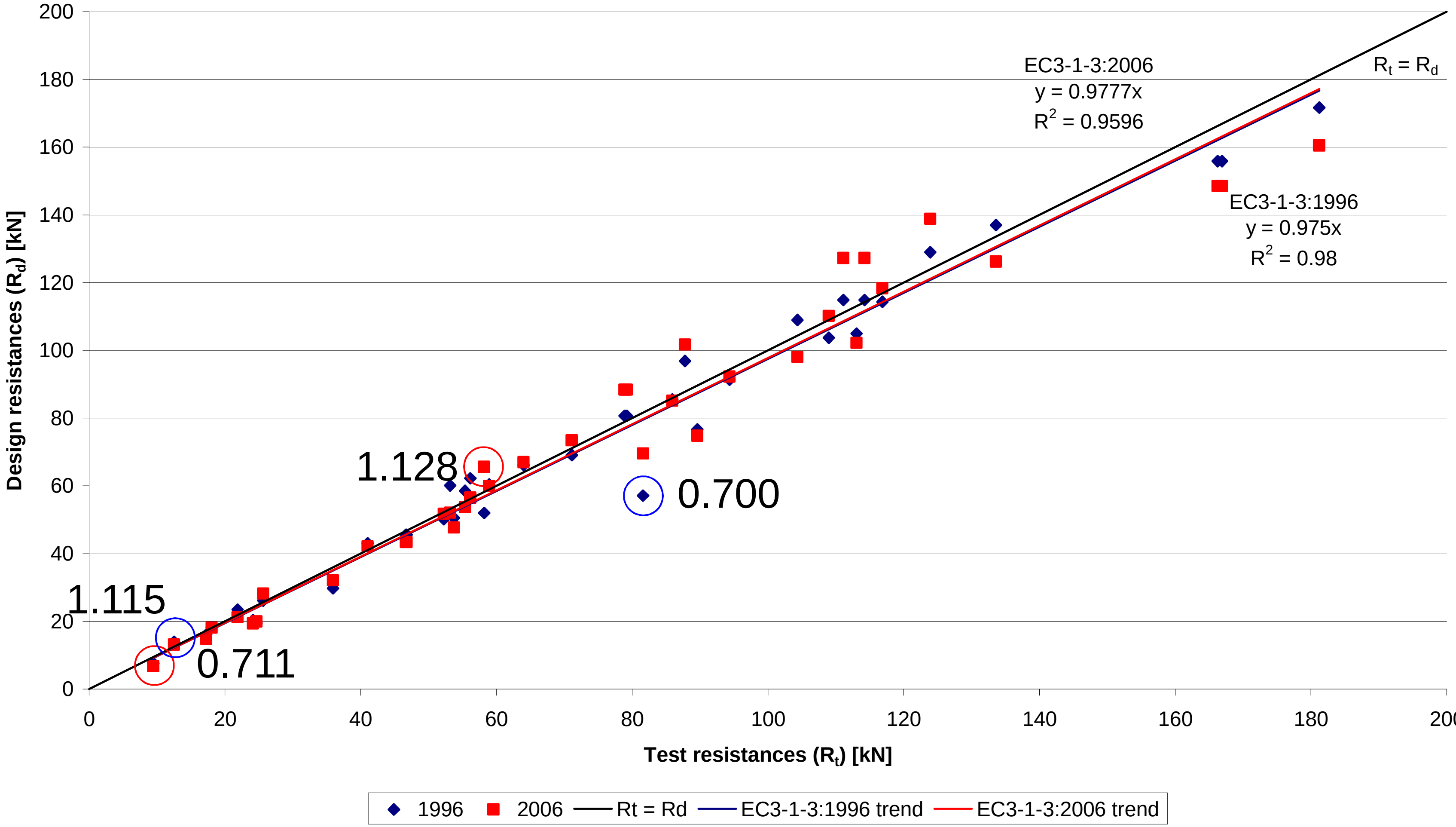


C-section members - evaluation

- Failure mode identification
- Test-based design resistances
  - one test leads to conservative result: $R_{adj}/R_d \sim 1.5$
  - tendencies of double arrangements
  - „family of tests”: effect of eccentricity
- Design codes
  - ENV EC3-1-3:1996 (pre-standard)
  - MSZ EN EC3-1-3:2006 (operational standard)

C-section members - evaluation

CompressionC, SimpleC, C, Brace



C-section members - design

EC3: interaction of flexural buckling and bending

EC3-1-3:1996

$$\frac{N_{Ed}}{\chi_{\min} \cdot f_{yb} \cdot A_{eff} / \gamma_{M0}} + \frac{\kappa_z \cdot (\boxed{M_{z,Ed}} + \Delta M_{z,Ed})}{f_{yb} \cdot W_{eff,z,com} / \gamma_{M0}} \le 1$$

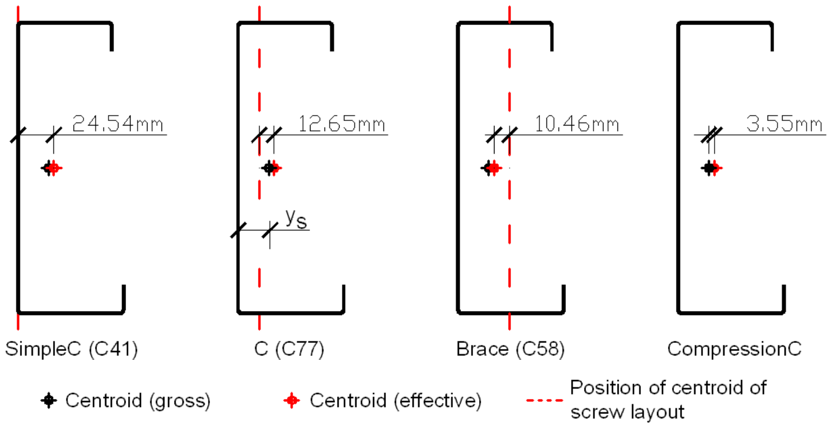
$$M_{z,Ed} = N_{Ed} \cdot e_{nom}$$

EC3-1-3:2006

$$\left(\frac{N_{Ed}}{N_{b,Rd}}\right)^{\boxed{0.8}} + \left(\frac{M_{Ed} + \Delta M_{Ed}}{M_{b,Rd}}\right)^{\boxed{0.8}} \le 1$$

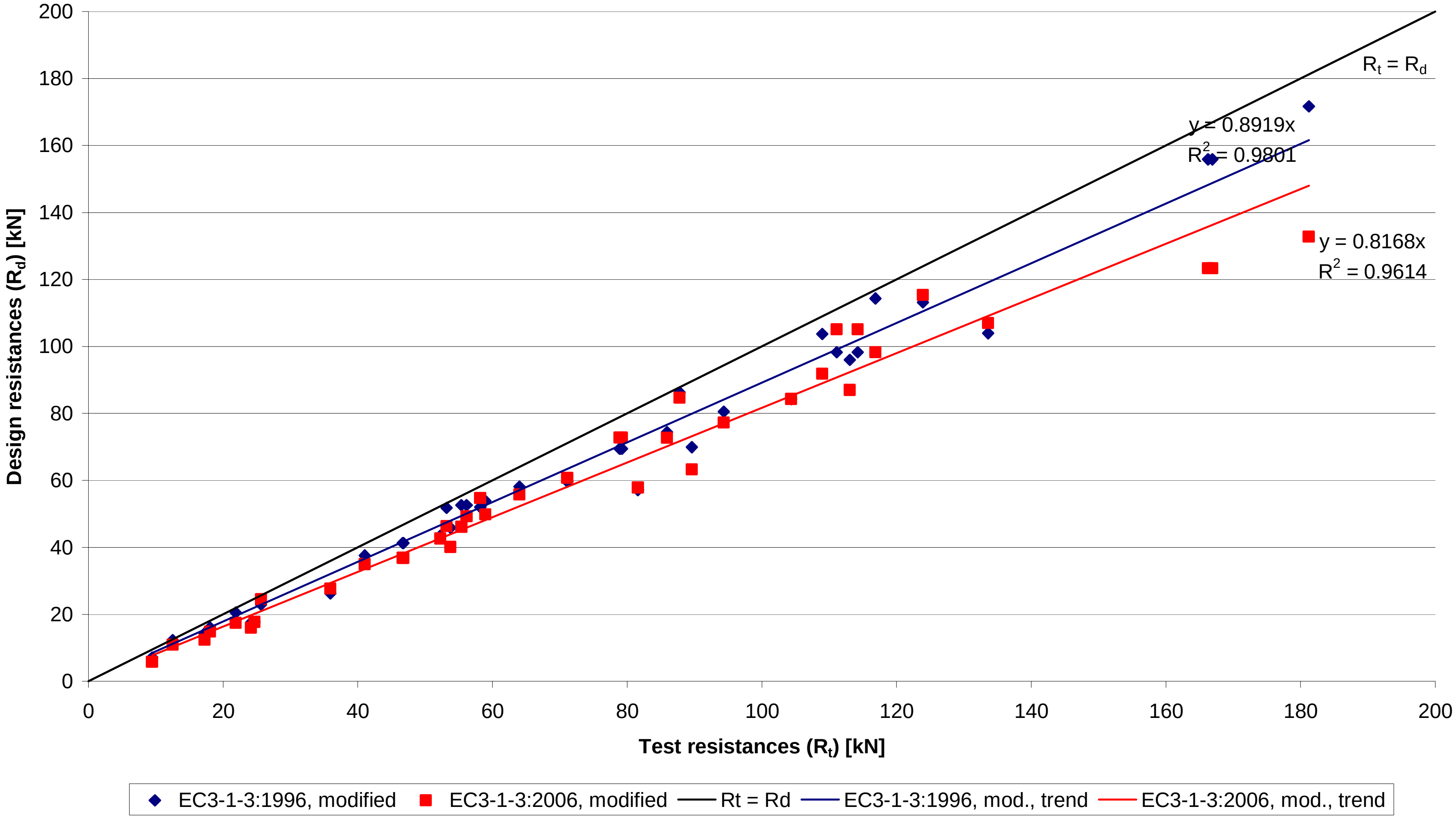
$$e_{\mathrm{mod}} = 1.4 \cdot e_{nom}$$

$$e_{\mathrm{mod}} \ge 0.4 \cdot y_S$$



$$\left(\frac{N_{Ed}}{N_{b,Rd}}\right)^{\boxed{0.65}} + \left(\frac{M_{Ed} + \Delta M_{Ed}}{M_{b,Rd}}\right)^{\boxed{0.65}} \le 1$$

C-section members - design



C-section members - design

- C-section laterally supported by hat sections

$$\frac{N_{Ed}}{f_{yb} \cdot 0.5 \cdot A_{eff} / \gamma_{M1}} \leq 1.0$$

- Doubled members

$$\frac{N_{Ed}}{\chi_{\min} \cdot f_{yb} \cdot A_{eff} / \gamma_{M1}} + \frac{\kappa_z \cdot (M_{z,Ed} + \Delta M_{z,Ed})}{f_{yb} \cdot W_{eff,z,com} / \gamma_{M1}} \leq \alpha$$

Arrangement	α
IC Column	0.8·L+1.0, L length of member [m]
CC	1.8
CU	1.3, if C-section is loaded 1.8, if U-section loaded
IC Brace	2.5

Thesis 1

I worked out and completed an experimental test program on compression members made of cold-formed C-sections with cross-sectional configurations and supporting conditions, which were not analysed previously.

I determined and classified the stability behaviour of

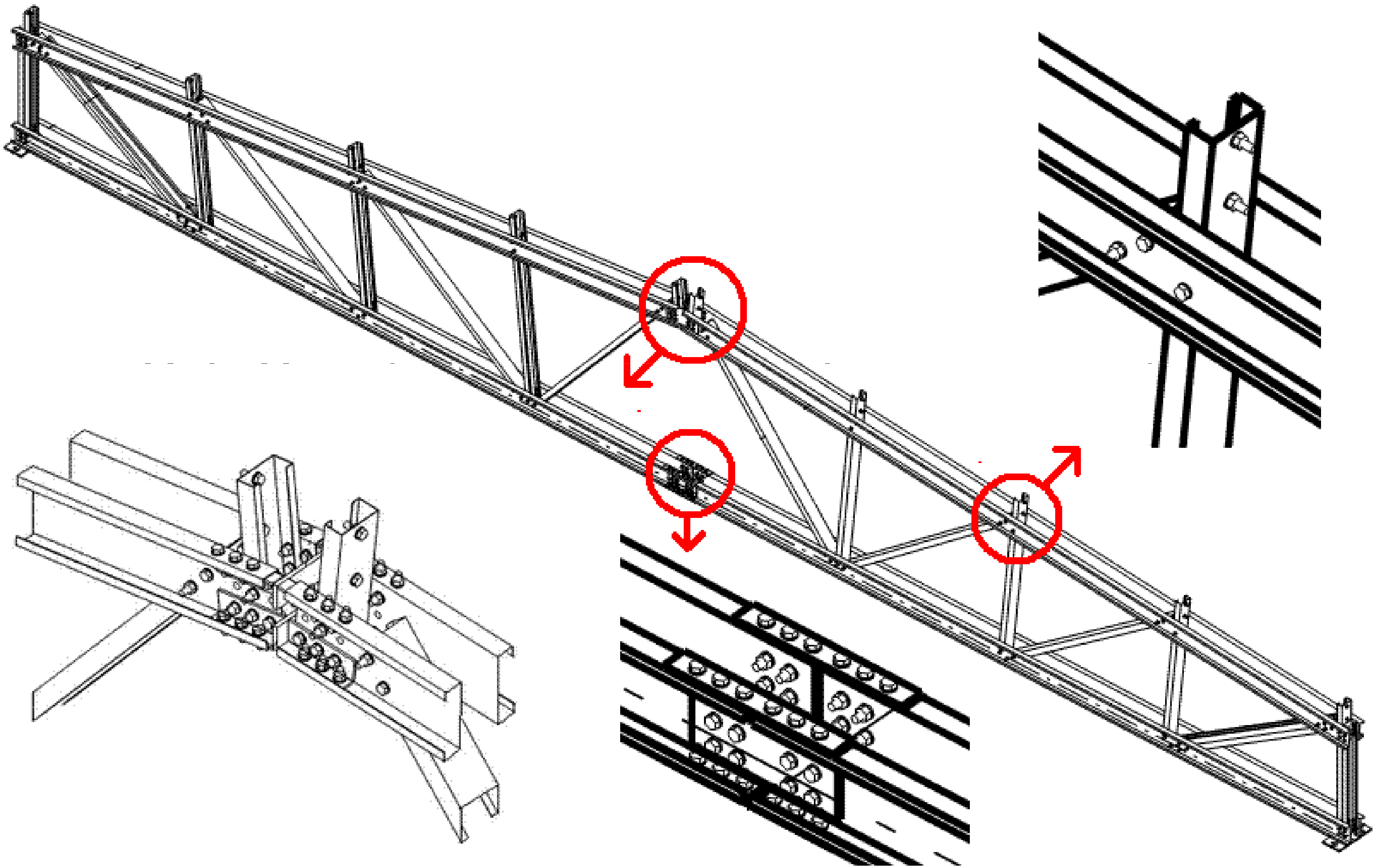
- single C-section members with load introduction in the web or in the web and the flanges using self-drilling screws, and load introduction in the flanges using bolts,
- single C-section members with load introduction in the web using self-drilling screws, laterally supported by hat sections in discrete points at one flange,
- members made of two C-sections in a back-to-back arrangement connected to each-other at the webs by self-drilling screws, with load introduction in the web or in the flanges using bolts,
- members made by sticking two C-sections in each-other, connected at the flanges by self-drilling screws, with load introduction in the webs or in the web and the flanges using self-drilling screws,
- members made by sticking a C- and a U-section in each-other, connected at the flanges by self-drilling screws, with load introduction in web of the C-section and the flanges using self-drilling screws.

Thesis 2

I developed Eurocode-based design methods for the members studied in the laboratory tests based on the comparative analysis of the test-based design resistances and behaviour modes.

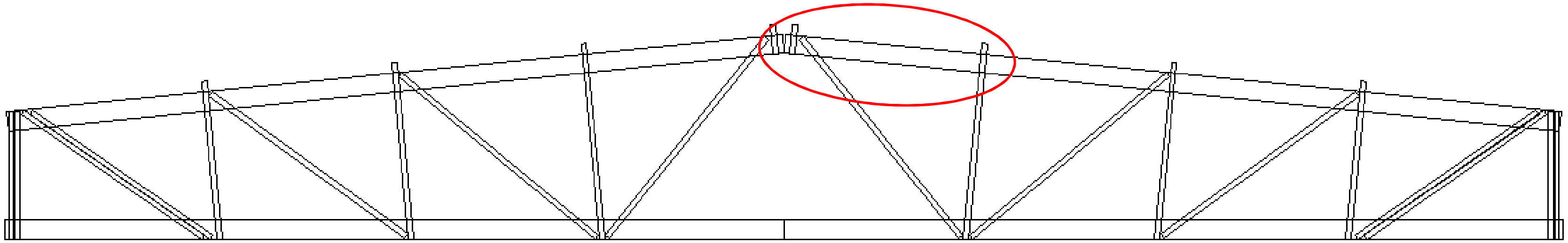
- I defined the eccentricity to be taken into account in the design of single C-section members without lateral support,
- I defined the interaction formula of single C-section members without lateral support in compression and bending about the weak axis,
- I developed a design method for single C-section members laterally supported at one flange,
- I derived the design resistances of members with complex cross-sectional arrangement on the basis of the design resistance of single members.

Truss system



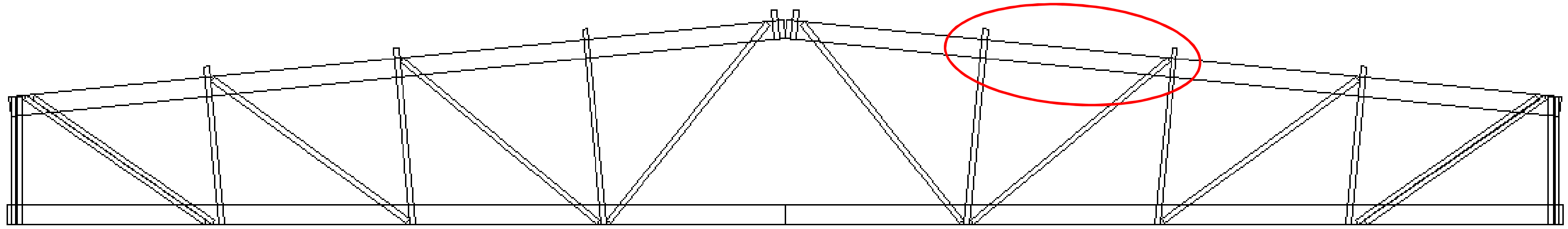
Truss system – test setup

Truss system – Test 1



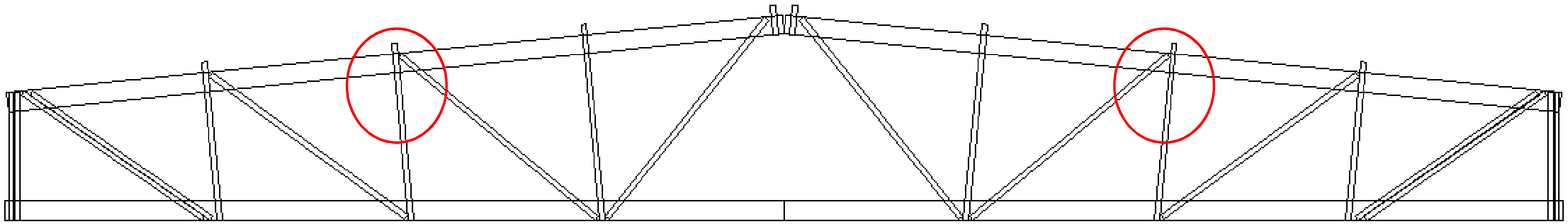
failure in the upper chord – interaction of flexural buckling and bending

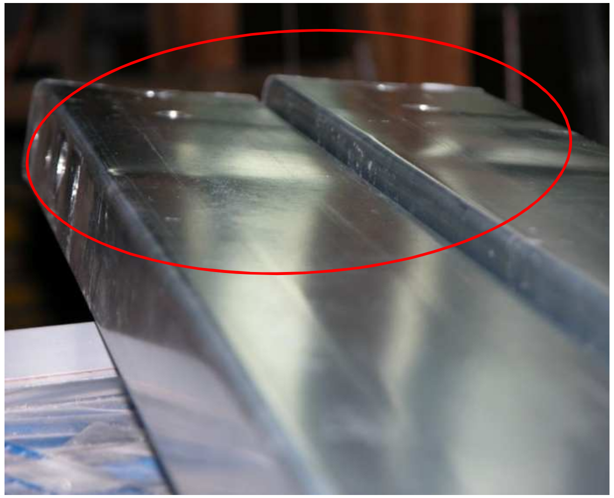
Truss system – Test 3



failure in the upper chord – global buckling of a built-up member

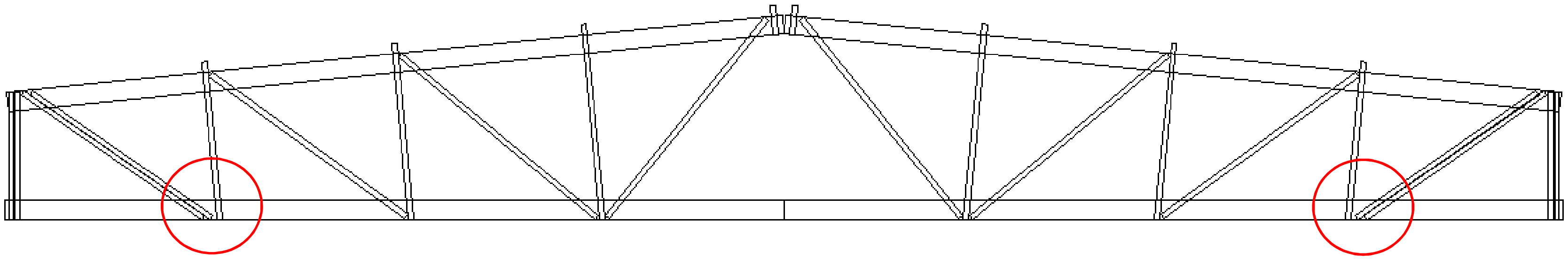
Truss system – Test 4





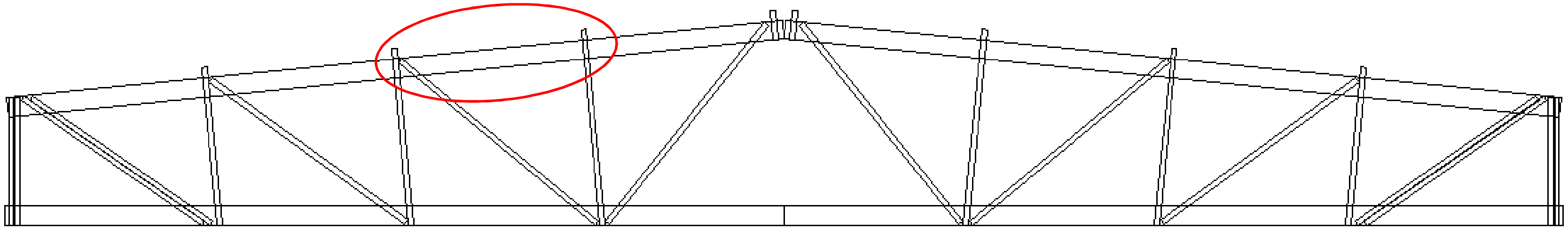
failure in compression brace members – interaction of compression and bending

Truss system – Test 5



failure if the lower chord joints next to the support – interaction of shear buckling and tension

Truss system – Test 5



failure in the upper chord – interaction of flexural buckling and bending

Truss system – design

- Global analysis
  - 2D beam FE model verified based tests results
- Design resistance of a chord member
  - reduced out-of-plane eccentricity

$$\frac{N_{Ed}}{\chi_{\min} \cdot f_{yb} \cdot A_{eff} / \gamma_{M1}} + \frac{\kappa_{LT} \cdot (M_{y,Ed} + \Delta M_{y,Ed})}{\chi_{LT} \cdot f_{yb} \cdot W_{eff,y,com} / \gamma_{M1}} + \frac{\kappa_z \cdot (0.5 \cdot M_{z,Ed} + \Delta M_{z,Ed})}{f_{yb} \cdot W_{eff,z,com} / \gamma_{M1}} \leq 1$$

- Design resistance of brace member
  - additional in-plane eccentricity

$$\frac{N_{Ed}}{A_{eff} \cdot f_{yb} / \gamma_{M0}} + \frac{N_{Ed} \cdot e_{add} + M_{z,Ed} + \Delta M_{z,Ed}}{W_{eff,z,com} \cdot f_y b / \gamma_{M0}} \leq 1$$

$$e_{add} = max(8\ mm,\ 0.2 \cdot b_1)$$

Truss system – design

- Design resistance of joints
  - shear buckling failure

$$V_{b,Rd} = \frac{\chi_w \cdot f_y \cdot A_{v,eff}}{\sqrt{3} \cdot \gamma_{M5}}$$

χ_w with $k_\tau = 5.34$

$A_{v,eff}$ with $k_\sigma = 4$ if compression chord member, otherwise $A_{v,eff} = A_{v,g}$

  - joint – chord member interaction

$$N_{0,Rd} = \left[\left(A_{0,eff} - A_{v,eff} \right) \cdot f_y + A_{v,eff} \cdot f_y \cdot \sqrt{1 - \left(V_{Ed} / V_{b,Rd} \right)^2} \right] / \gamma_{M5}$$

$A_{0,eff}$ A_{eff}, if compression chord member, otherwise A_g

Thesis 3

I completed an experimental test program on prototypes of a truss system made of cold-formed C-sections. The specialities of the structural arrangement are: i) the chord members consist of two C-sections in a back-to-back arrangement, with a distance equal to the web height of the brace members, ii) brace members are stuck between the chord members, iii) structural joints are made using fitted bolts, iv) brace members may be of single sections or doubled in a back-to-back arrangement.

I determined and characterized the behaviour of the truss based on the following observed failure modes:

- interacting out-of-plane global and local buckling of compression chord members,
- interacting out-of-plane global and local buckling of built-up compression chord members,
- cross-section failure of compression brace members at the element end,
- cross-section failure of brace-to-chord and chord-to-chord structural joints.

Based on the observed behaviour I defined constructional rules regarding the detailing of the joints ensuring favourable structural behaviour.

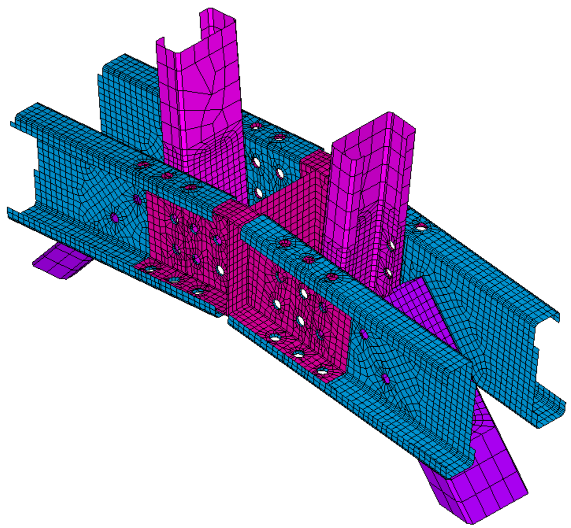
Thesis 4

I developed Eurocode-based design method for the structural members of the trusses studied in the laboratory tests based on the observed behaviour and failure modes and validated them based on the measured load-bearing capacities.

- I defined the modelling level to be applied in global analysis and verified the model based on the results of strain and deflection measurements,
- I defined the magnitude of eccentricity to be taken into account in the design of compression chord and brace members,
- I developed a design method to calculate the design resistance of structural joints, taking into account the interaction of structural members and joints.

Numerical model

- Aim: virtual experimenting
  - C-section compression member (SimpleC)
  - Truss (Test 1, 5)
- Modelling level: GMNIA
  - surface model
  - material model based on tensile tests
  - equivalent geometrical imperfections
- General approach
  - „Exact" geometrical modelling
  - Elements used
  - Contact surfaces

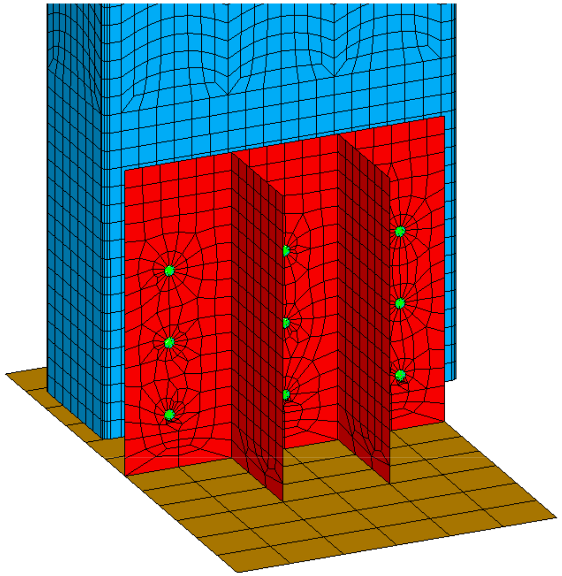


Numerical model

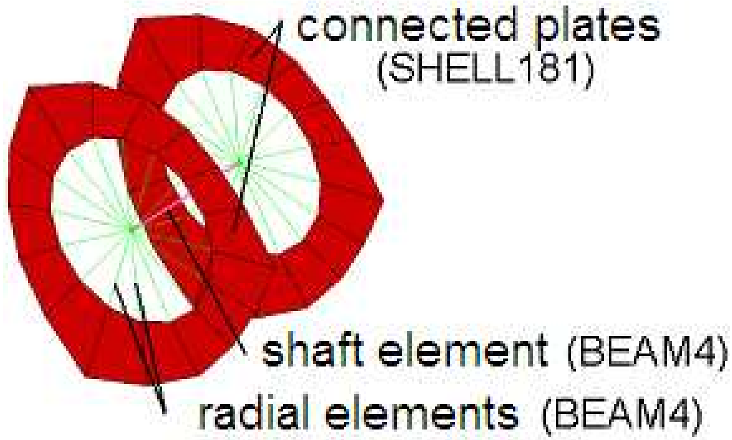
- Connections
  - non-rigid connector elements
  - bolts: shear and bearing
  - self-drilling screws: tilting, pull-out
  - should be compatible with shell elements
- Imperfections
  - many possible approaches, but no standardized method

Numerical model - SimpleC

- Self-drilling screws
  - „beamstar"
  - calibrated by 2 parameters

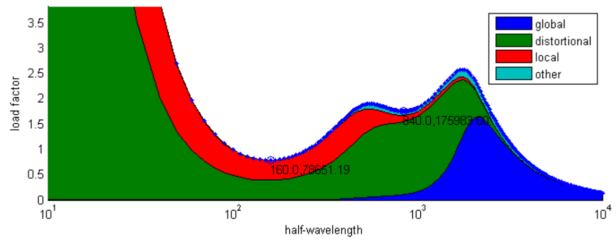


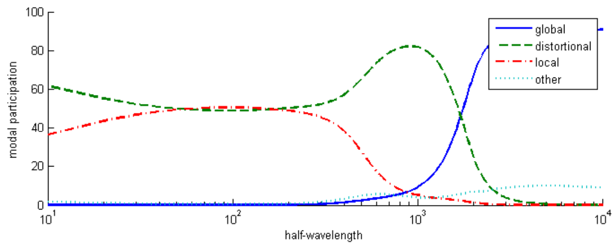
	area [mm^2]	Shear divider	Second moment of inertia [mm^4]	Torsional moment of inertia [mm^4]
Shaft	$r^2\pi$	70	$r^4\pi/4$	$r^4\pi/4$
Radial element	100	0	0.01	1



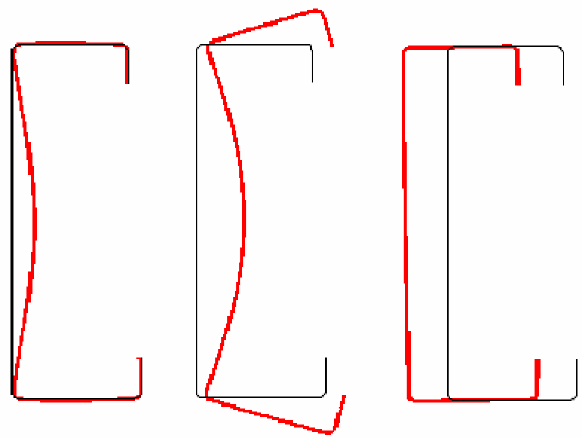
Numerical model - SimpleC

- Imperfections
  - shapes and wavelengths obtained from cFSM analysis
  - weight of modes is known
  - imperfection sensitivity analysis is possible

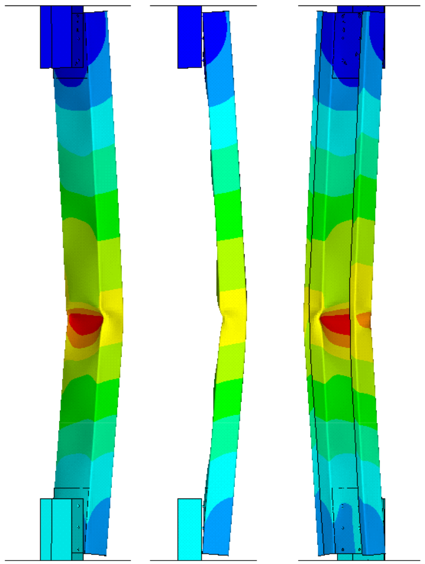


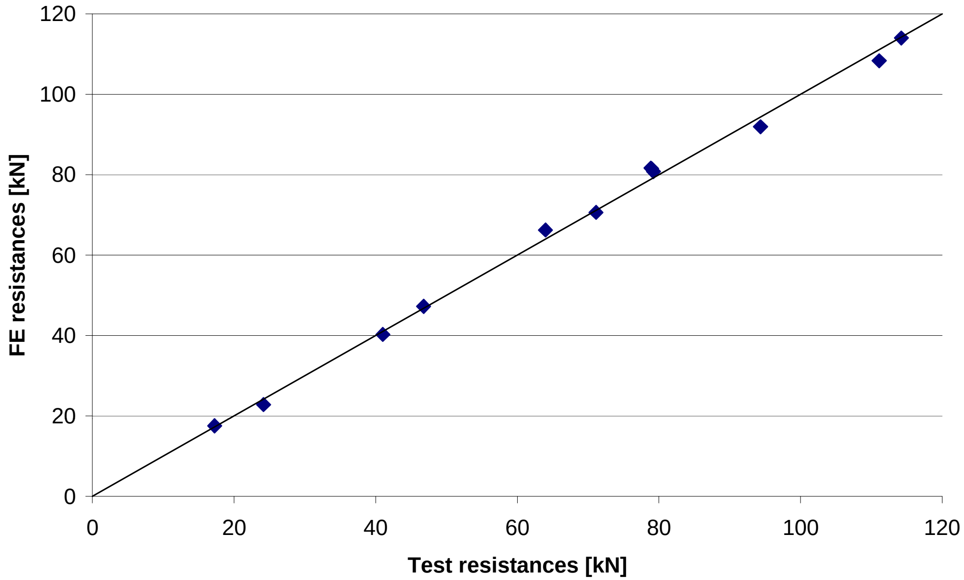


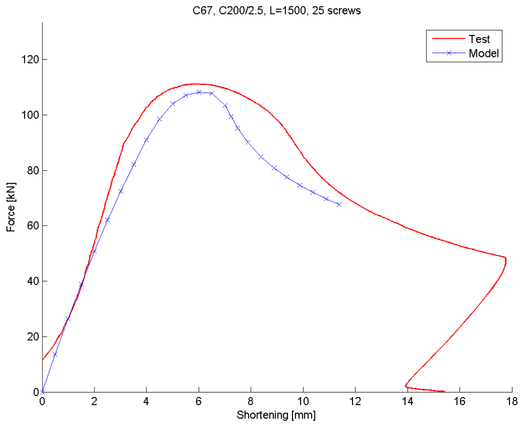
shape	local	global
amplitude [mm]	3	-6
half-wavelength	150 mm	member length

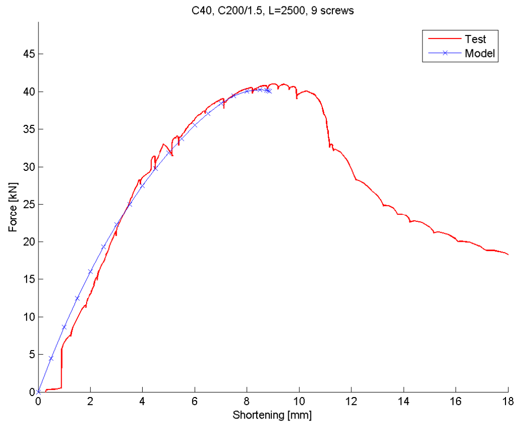


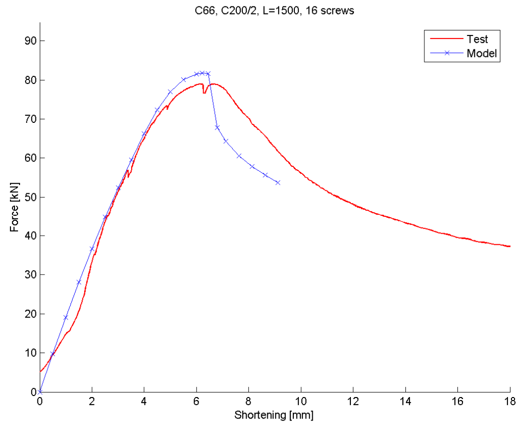
Numerical model - SimpleC





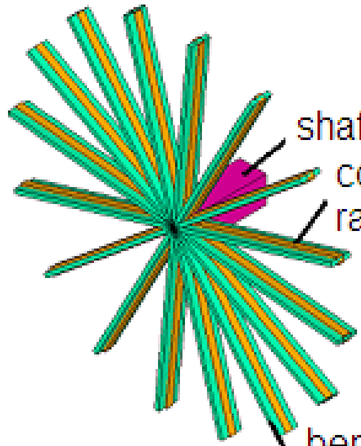






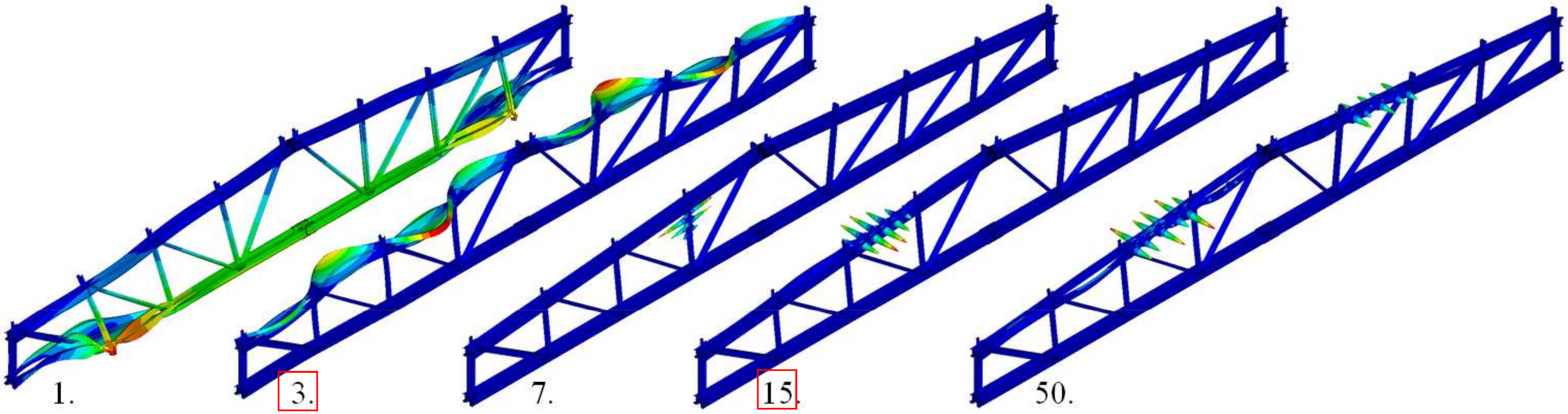
Numerical model – truss

- Bolts
  - modified „beamstar"
  - calibrated by 1 parameter



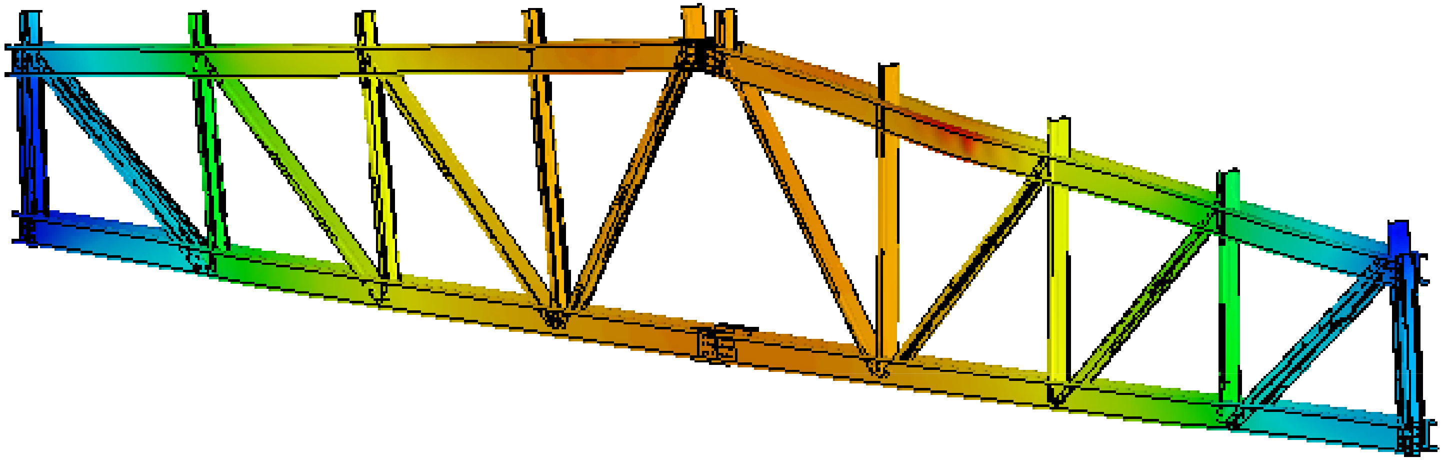
	element type	area [mm^2]	shear divider	I_z [mm^4]	I_y [mm^4]	I_x [mm^4]
Test 1 Test 5	BEAM4	$r^2\pi$	0	$r^4\pi/4$	$r^4\pi/4$	$r^4\pi/4$
	BEAM44	10^{-3}	0	100	0.1	0
Test 1	LINK10	0.4	-	-	-	-
Test 5	LINK10	1.0	-	-	-	-

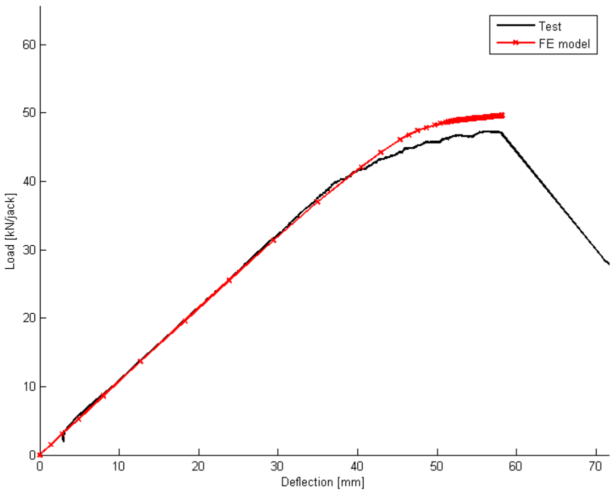
Numerical model – truss

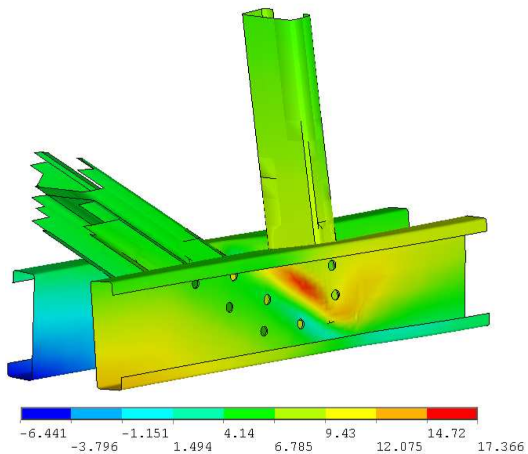


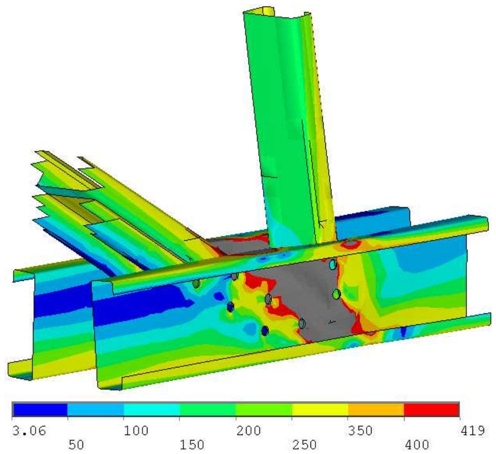
applied imperfections	
shape Nr.	amplitude [mm]
3	7.5
15	1.5

Numerical model – truss









Thesis 5

I developed shell finite element models of the single C-section members with load introduction in the web using self-drilling screws and of the truss girders, both capable of carrying out virtual experiments by materially and geometrically nonlinear analysis. The specialities of the models are the modelling of equivalent geometrical imperfections and modelling connector elements.
I generated the imperfections of the models as follows:

- in the case of the single C-section members using the constrained finite strip method enabling the control of the weight of pure – local, distortional, global – buckling modes in the generated imperfect shape,
- in the case of the truss girders based on selected eigenshapes of the model.

I developed models of connector elements used in the laboratory tests, compatible with shell elements and capable of following the structural behaviour as: tilting and pull-out in the case of self-drilling screws, shear and bearing in the case of bolts.
I used the laboratory test results to determine the stiffness parameters of the models of the connector elements, and the shape and amplitude of imperfections to be applied on the model.

Acknowledgement

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