

Improvement methods for Eurocode based design – numerical study and test result evaluation



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Introduction

1. *Specialties of the HSS structures, consideration in the design approaches*
2. *Literature review*
3. *Research methodology*
4. *Buckling curve development for HSS closed section columns*
 1. *Experimental approach*
 2. *Deterministic FEM based approach*
 3. *Stochastic FEM based approach*
 4. *Comparison of the three methods*

Introduction – research aims

Application of HSS (S500 – S960):

- Widely used in vehicles and ships
- Small application for civil engineering structures

↓
increasing tendency

Limitation of the wide application:

- relatively high cost
- limited design background

→ additional investigations,
→ special structural behaviour
→ standardization

↓
*Wide research activities : West-European Universities (Aachen, Tampere, Lulea, Stuttgart, Coimbra),
in the USA and Asia*

↓
+ BME Department of Structural Engineering (2012 - ...)

- RFCS research projekt: RUOSTE Rules on High Strength Steel *European standardization*
- GINOP research projekt: SteelBeam - Innovative, long-span, welded beam development

Improvement of Hungarian application

EN 10149-2 ^{a)}	1,5 mm ≤ t ≤ 8 mm		8 mm < t ≤ 16 mm	
	f_y [N/mm ²]	f_u [N/mm ²]	f_y [N/mm ²]	f_u [N/mm ²]
S 500MC	500	550	500	550
S 550MC	550	600	550	600
S 600MC	600	650	600	650
S 650MC	650	700	630	700
S 700MC	700	750	680	750
a) Verification of the impact energy in accordance with EN 10149-1 Clause 11, Option 5 should be specified.				

Research focuses

Current application:

1. Large span bridges



Tokyo Gate Bridge – BHS500 és BHS700

In Hungary: S420- S460

(in launching devices: S700)

Weight reduction

Section reduction

Research focus points:

- *Fatigue assessment*
- *Stability of welded sections (plate buckling)*

2. Truss surface structures



HSS welded or cold formed box sections

- *Flexural buckling of welded box sections*

Advantages of HSS structures

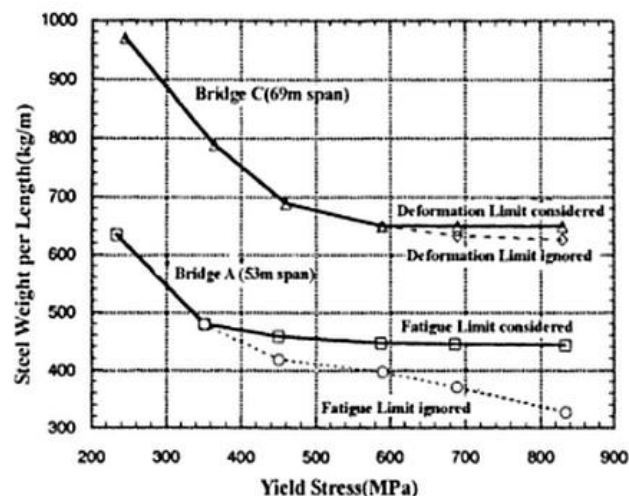
- Smaller self-weight and material cost,
- Slender structures,
- Larger span, reduced number of supports,
- Reduced erection costs,
- Easier transportability and erection,
- Reduced maintenance costs, better corrosion behaviour,
- Good weldability (M/ML materials – thermomechanically rolled materials),
- Negative moment reduction for bridge launching (erection phases)

Advantageous for bridges

Results of the cost calculations:

1. Smaller spans: > **S355 fatigue is dominant**
2. Larger spans: > **S600 SLS dominant**
3. Economical in **hybrid girders, composite structures**)

Economical calculations



Properties of HSS material

Development from 1950



High yield strength (>500 MPa)

Wronger weldability, decreased ductility

Nowaday materials



*High yield strength + corrosion prot. + larger ductility
/0,15% carbon content/*

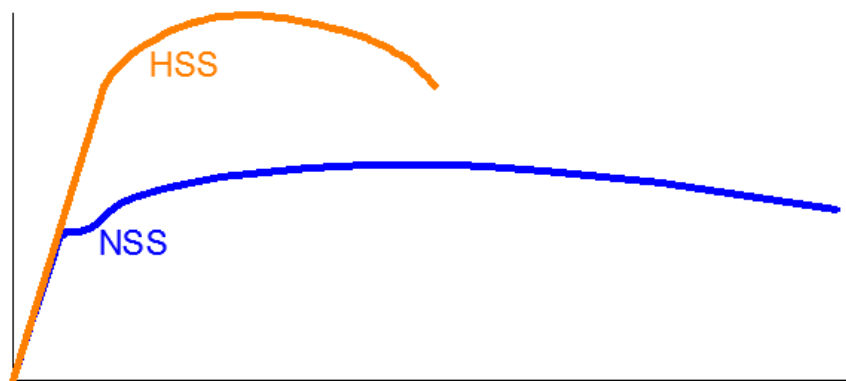


*Applicable for civil engineering
structures*



*Modified material properties should be
considered in the design*

1. Stress – elongation diagram



- Higher yield strength
- No yield plateau
- Yield strength definition: 0,2% residual strains

Stability analyzis



Properties of HSS material

2. Smaller hardening effect (f_u/f_y arány)

3. Smaller ductility

S235 – S460 (EN1993-1-1)

- $f_u / f_y \geq 1,10$;
- elongation at failure not less than 15%;
- $\epsilon_u \geq 15\epsilon_y$, where ϵ_y is the yield strain ($\epsilon_y = f_y / E$).

S500 – S700 (EN1993-1-12)

- $f_u/f_y \geq 1,05$;
- elongation at failure not less than 10 %;
- $\epsilon_u \geq 15f_y/E$.

S960

No standard rules

Not always satisfied

BME experiments (37 specimens):

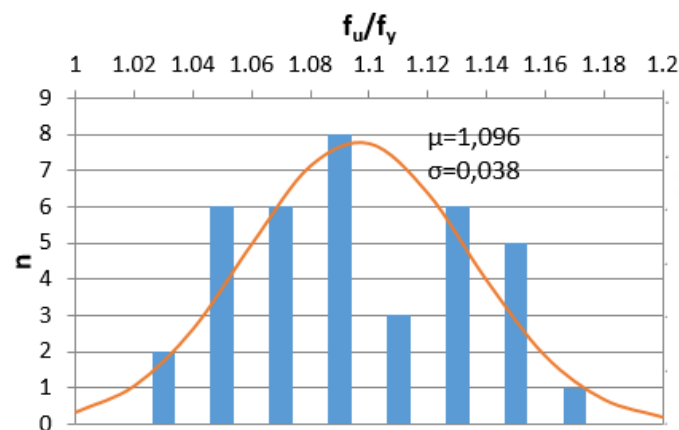
- 37 specimens:
22 (~60%) specimens: $f_u/f_y < 1,1$
4 (~10%) specimens: $f_u/f_y < 1,05$



Current design methods are validated based on these properties



Enhancement is needed



Research aim – buckling curve development for HSS section

Results:

Improvement of the flexural buckling curve selection method

Cross section		Limits	Buckling about axis	Buckling curve		S500-S700	S960
				S 235 S 275 S 355 S 420	S 460		
Rolled sections 	$h/b > 1,2$	$t_f \leq 40 \text{ mm}$	y - y z - z	a b	a ₀ a ₀		
		$40 \text{ mm} < t_f \leq 100$	y - y z - z	b c	a a		
	$h/b \leq 1,2$	$t_f \leq 100 \text{ mm}$	y - y z - z	b c	a a		
		$t_f > 100 \text{ mm}$	y - y z - z	d d	c c		
Welded I-sections 		$t_f \leq 40 \text{ mm}$	y - y z - z	b c	b c		
		$t_f > 40 \text{ mm}$	y - y z - z	c d	c d		
Hollow sections 		hot finished	any	a	a ₀		
		cold formed	any	c	c		
Welded box sections 		generally (except as below)	any	b	b		
		thick welds: $a > 0,5t_f$ $b/t_f < 30$ $h/t_w < 30$	any	c	b		

Application of higher steel grades allows to use higher buckling curves!

Research program

Detailed research strategy (separately for welded and cold-formed sections):

1. ***literature review*** on buckling tests of hollow section HSS columns,
2. ***literature review*** on HSS residual stress measurements,
3. ***residual stress measurements*** on welded and cold formed sections with different b/t ratios and different steel grades (S420, S460, S500, S700 and S960),
4. evaluation of the ***test results*** and design residual stress model development for HSS hollow section members (separately for welded and cold-formed sections),
5. measurement of the ***out-of-straightness imperfection*** on the buckling test specimens,
6. ***flexural buckling tests*** on welded and cold-formed HSS members with different global slenderness and different steel grades (S420, S460, S500, S700 and S960),
7. ***Deterministic and stochastic numerical analysis*** on welded and cold-formed HSS members
8. ***proposal for design column buckling curve*** for cold formed and welded HSS hollow section members based on statistical evaluation of experimental and numerical test results.



Literature review

Previous experiments

Literature review

- Collected experiments from 8 research papers
- 70 used test result
- Yield strength is between 337 and 973 MPa
- Cold-formed and welded; carbon and stainless steel specimens

Author	Number of specimens	Yield strength [MPa]	Material type	Manufacturing process
Young, Lui	24 (24)	486-707	SS	cold-formed
Young, Lui	3 (3)	448-503	SS	cold-formed
Liu, Young	10 (12)	337-444	SS	cold-formed
Theofanous, Gardner	17 (20)	586-755	SS	cold-formed
Degée, Detzel, Kuhlmann	6 (6)	390	CS	welded
Pavlovčič, Froschmeier, Kuhlmann, Beg	4 (4)	373	CS	welded/cold-formed
Ban, Shi, Shi, Wang	4 (5)	492-532	CS	welded
Ban, Shi, Shi, Bradford	2 (3)	973	CS	welded
Σ	70 (77)	337-973		

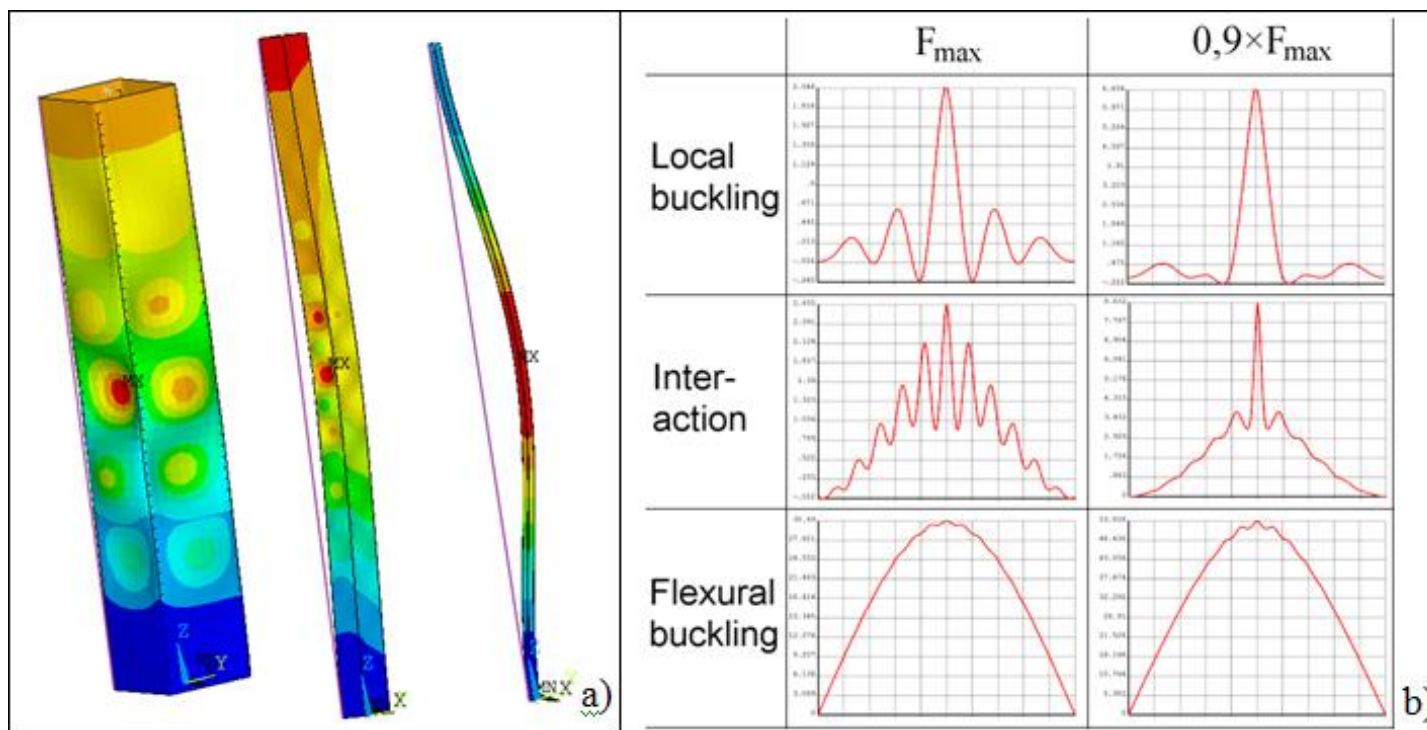
used specimens

(total specimens of the paper)

stainless or carbon steel

Failure mode separation

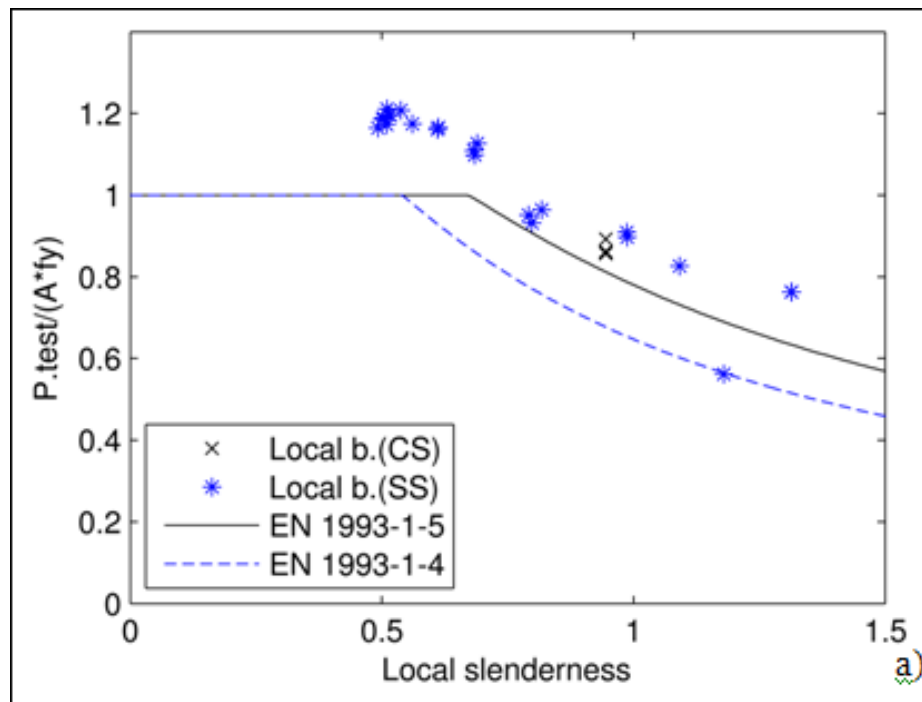
- The separation of the different failure modes is the key by the evaluation of the experimental results.
- Possible failure modes: local buckling, interaction of local and flexural buckling and flexural buckling.
- Separation made using numerical model.



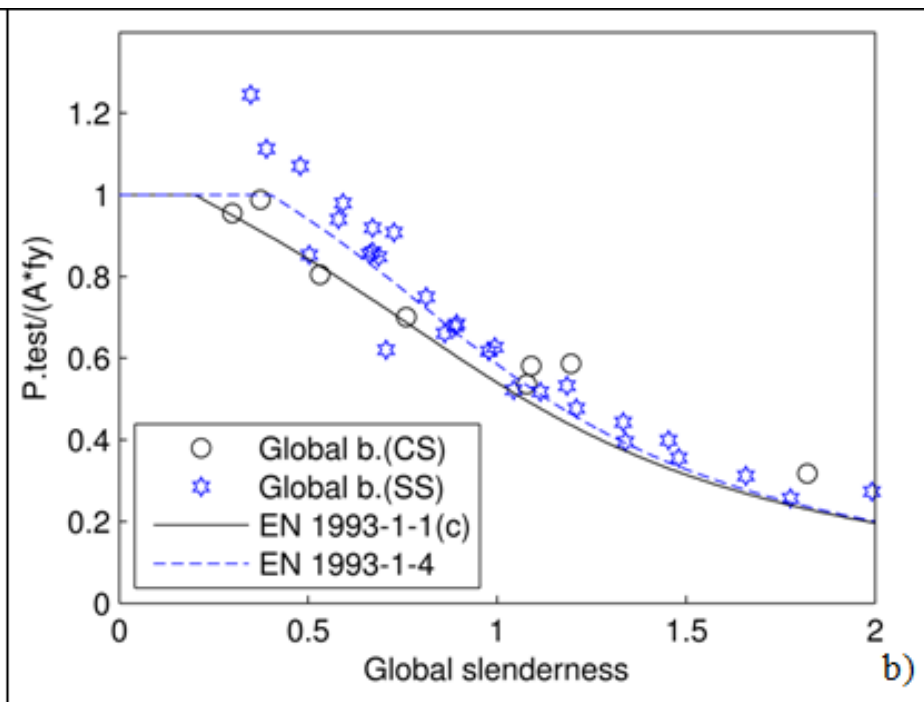
Discussion of the previous test results

- 27 specimens with local buckling, 37 specimens with flexural buckling, 6 specimens with interaction type failure mode
- The experimental resistances are mainly higher than the suggestions from the corresponding buckling curves of Eurocode

Local buckling

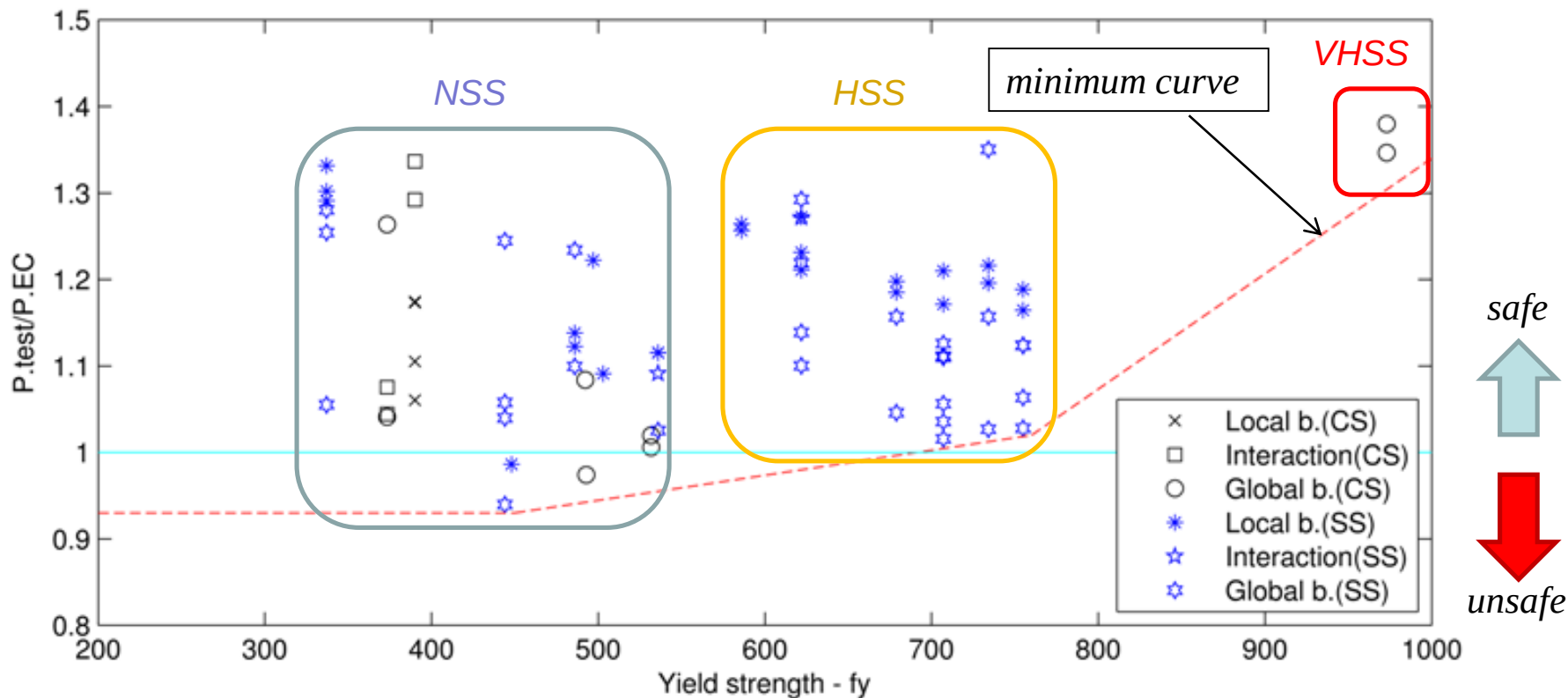


Flexural buckling



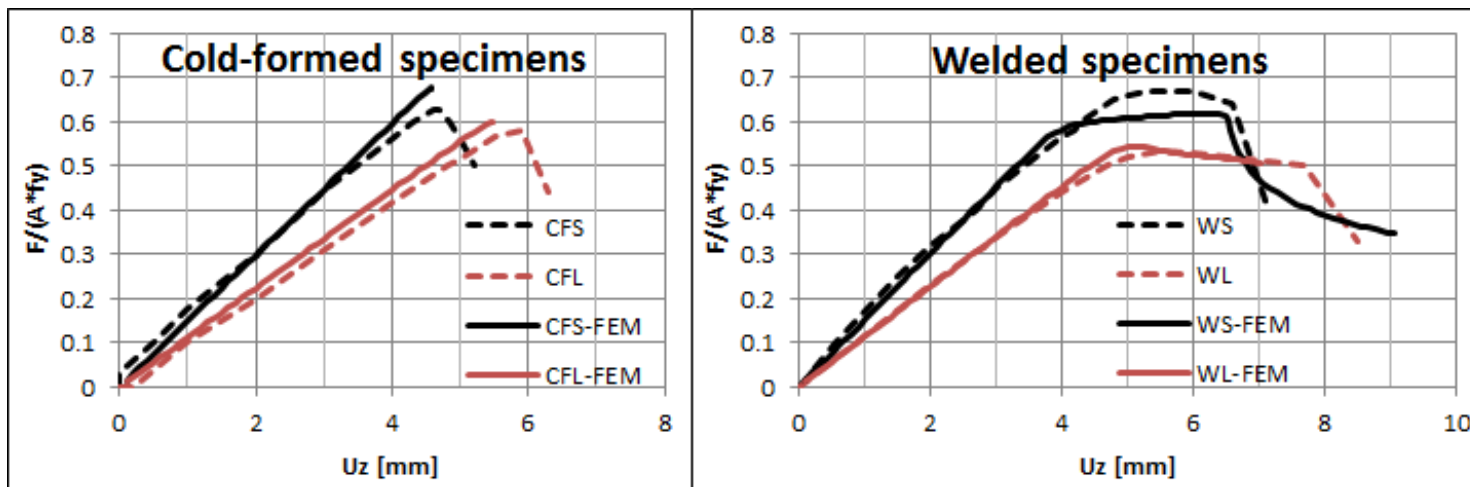
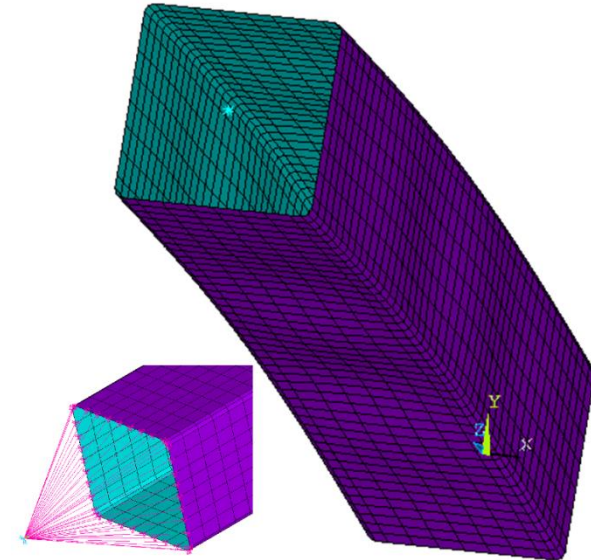
Effect of the yield strength

- The difference between experimental resistance and the design resistance of Eurocode are evaluated in function of yield strength.
- The considered yield strength are taken from the coupon test results of the actual experiment.



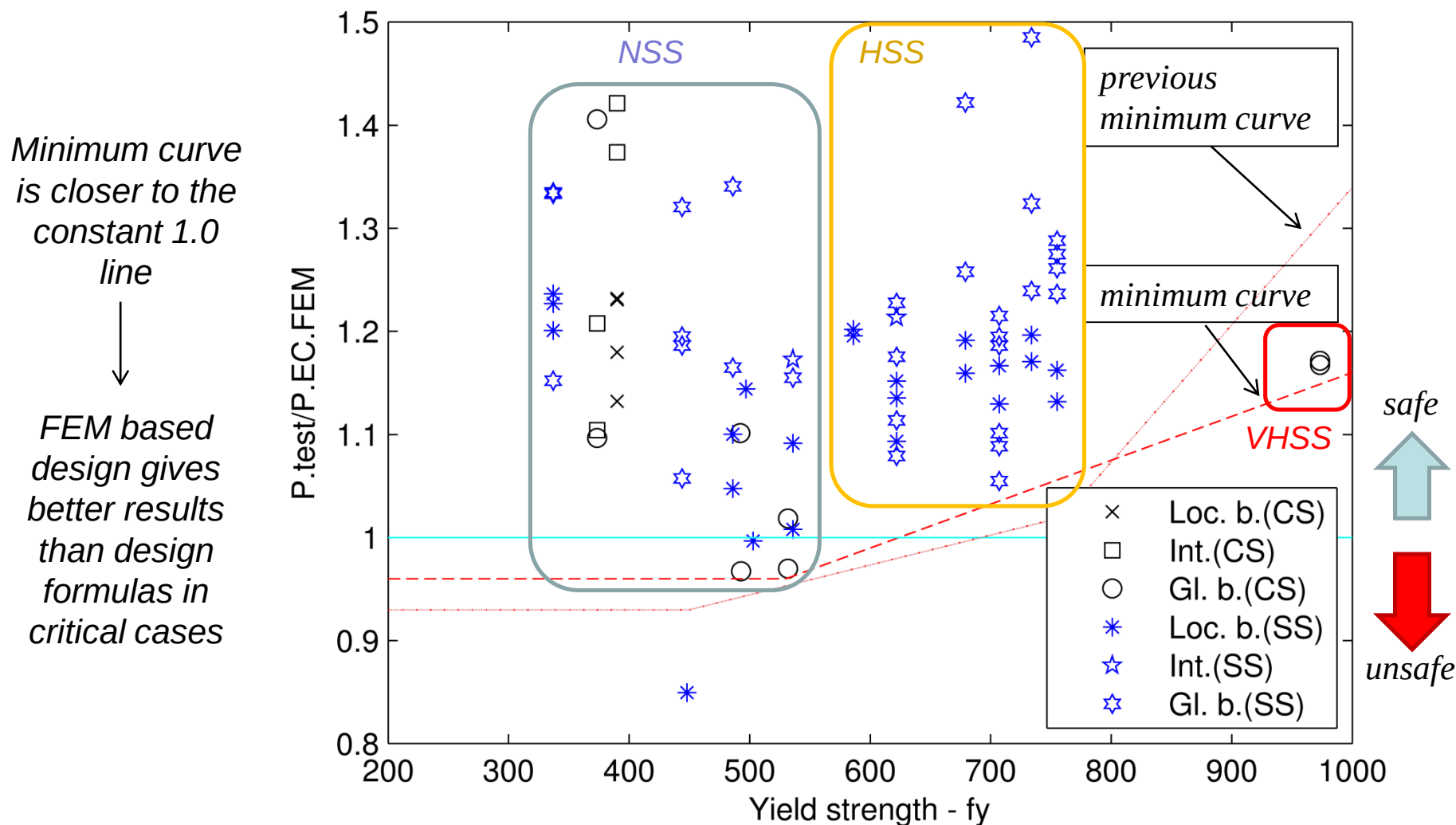
Numerical model description

- Shell model using ANSYS software
- GMNI analysis:
 - Nonlinear analysis
 - Included global and local geometric imperfection
 - Included measured residual stress if able
 - The material model is based on examined coupon tests
- Verified by experimental results (Degée et al.)



Assessment of finite element based design

- Using equivalent geometric imperfection (both local and global)



Conclusion for high strength carbon steel

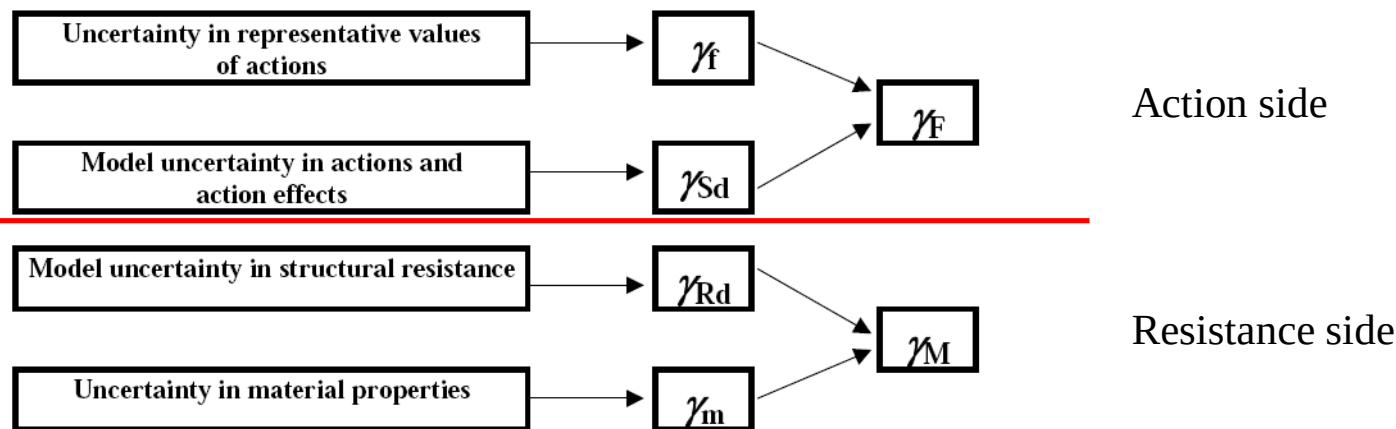
- The **design methods give smaller resistances compared to the test results** using high strength carbon steel columns in case of flexural buckling.
- The **FEM based design method gives higher resistances** than the analytical **design method of Eurocode** in case of very high strength steel, thus the numerical design method gives closer results to the test results in case of very high strength steel.
- However, there are only **very few available** axially compressed **high strength steel** hollow section **experimental results** in the literature, so **more experiments** should be carried out.
- *RFCS kutatási projekt: RUOSTE Rules on High Strength Steel*
- *GINOP projekt: SteelBeam - Innovatív, nagyfeszítávolságú, hegesztett acél gerendafejlesztés*



Literature review

Statistical evaluation method

General overview



$$\gamma_{M1}^{**} = \gamma_m \cdot \gamma_{Rd}^{**} \quad \text{Required partial safety factor}$$

$$F_{Rd,new} = \frac{F_R}{\gamma_{M1}^{**}} = \frac{2 \cdot \sqrt{n \cdot M_{plf} \cdot t_w \cdot \delta \cdot f_{yw}} + \delta \cdot t_w \cdot f_{yw} \cdot ss \cdot k_\alpha}{\gamma_K \cdot \gamma_{M1}} \quad \text{Resistance function}$$

γ_K : Modification factor to reach the required safety level
 γ_{M1} : Partial safety factor given in the Eurocode

Determination of γ_{Rd}^{**}

Based on EN1990 Annex D

1. step: Development of resistance model

$$F_R = 2 \cdot \sqrt{n \cdot M_{plf} \cdot t_w \cdot \delta \cdot f_{yw}} + \delta \cdot t_w \cdot f_{yw} \cdot ss \cdot k_\alpha$$

2. step: Comparison of experimental and theoretical values (Fig. 1)

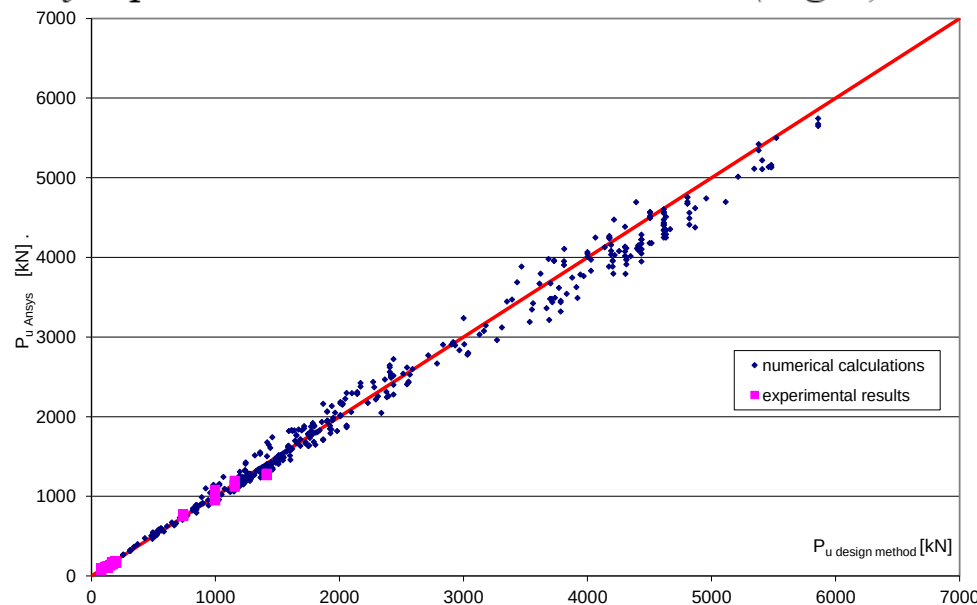


Fig. 1: Comparison of numerical calculations and design method.

3. step: Estimation of the mean value correction factor b

$$b = \frac{\sum F_{R,num} \cdot F_{R,design_method}}{\sum F_{R,design_method}^2} = 0.9777$$

4. step: Estimation of the coefficient of variation of the errors

error term for each value:
$$\delta_i = \frac{F_{R,num_i}}{b \cdot F_{R,design_method_i}}$$

logarithm of the error terms:
$$\Delta_i = \ln(\delta_i)$$

mean value of logarithm of the error terms:
$$\bar{\Delta} = \frac{1}{n} \cdot \sum_{i=1}^n \Delta_i = 0.0227$$

standard deviation of the error terms:
$$s_{\Delta}^2 = \frac{1}{n-1} \cdot \sum_{i=1}^n (\Delta_i - \bar{\Delta})^2 = 0.0359$$

coefficient of variation of the error terms:
$$V_{\delta} = \sqrt{\exp(s_{\Delta}^2) - 1} = 0.06$$

5. step: Determination of the coefficient of variation of the basic variable of resistance model

According to EN1990 [1] the material and geometrical uncertainty should be taken here into account. The material property is handled separately, but the geometric uncertainty is considered. The mean value and coefficient of variation of the geometrical parameters are needed to determine this parameter. Two different proposals are found in the literature to solve it.

Method 1: Own measurements

	plate thickness		plate width	
t_{nom} [mm]	20	30	225	500
n [-]	104	38	45	13
t_{mean} [mm]	20.44	30.01	225.00	499.33
S_X	0.1651	0.1115	0.5317	0.6513
V_{geom}	0.0081	0.0037	0.0024	0.0013
$V_{geom,mean}$	0.0059		0.0018	

Method 2:

Recommendations of "Joint
Committee of Structural Safety"

Method 3:

International literature:
diploma thesis of Gabeler

6. step: Coefficient of variation of the FE model

The value of V_{FEM} is calculated based on the experiments of Elgaaly and Seshadri [4] and based on the 12 own test results which are recalculated by numerical models. The calculation steps are the same as in the steps 3 and 4. Calculation for one specimen is detailed in Eqs. (10)-(15), and the result for all studied specimens can be found in Table 3.

$$b_{FEM} = \frac{\sum F_{R,exp} F_{R,num}}{\sum F_{R,num}^2} = 1.01924 \quad (10)$$

$$\delta_{FEM,i} = \frac{F_{R,exp}}{b_{FEM} \cdot F_{R,num}} \quad (11)$$

$$\Delta_{FEM,i} = \ln(\delta_{FEM,i}) \quad (12)$$

$$\bar{\Delta}_{FEM} = \frac{1}{n} \cdot \sum_{i=1}^n \Delta_{FEM,i} = 0.0054 \quad (13)$$

$$s_{\Delta,FEM}^2 = \frac{1}{n-1} \cdot \sum_{i=1}^n (\Delta_{FEM,i} - \bar{\Delta}_{FEM})^2 = 0.00046 \quad (14)$$

$$V_{FEM} = \sqrt{\exp(s_{\Delta,FEM}^2) - 1} = 0.0214 \quad (15)$$

EN1990 Annex D is developed for the evaluation of test results.

Numerical model has also uncertainties $\longrightarrow$ should be extra considered

7. step: *Determination of the partial factor*

Coefficient of variation of the whole resistance model can be calculated by Eqs. (16)-(18).

$$V_r^2 = (V_\delta^2 + 1) \cdot \left[\prod_{j=1}^n (V_{Xi}^2 + 1) \right] \cdot (V_{FEM}^2 + 1) - 1 \quad (16)$$

$$V_r^2 = (V_\delta^2 + 1) \cdot (V_{geom1}^2 + 1) \cdot (V_{geom2}^2 + 1) \cdot (V_{FEM}^2 + 1) - 1 \quad (17)$$

$$V_r^2 = (0.06^2 + 1) \cdot (0.005^2 + 1) \cdot (0.005^2 + 1) \cdot (0.0214^2 + 1) - 1 = 0.064 \quad (18)$$

Based on V_r an auxiliary variable can be calculated by Eq. (19) and the partial factor is obtained by Eq. (20).

$$Q = \sqrt{\ln(V_r^2 + 1)} = \sqrt{\ln(0.064 + 1)} = 0.064$$

$$\gamma_{Rd}^{**} = \frac{1}{b \cdot e^{-3.04 \cdot Q - 0.5 \cdot Q^2}} = 1.25$$

Determination of γ_m

In the FE calculations: mean value of geometrical parameters,
characteristic (nominal) value for the material properties.



material partial factors could solve this inconsistency

$$\gamma_m = \frac{f_{y,nom}}{f_{yd}} = \frac{f_{y,nom}}{f_{y,m} \cdot (1 - 1.64 \cdot V_{fy})}$$

Recommendations:

- International literature: Gabeler,
- recommendation of the JCSS,
- research work of L. da Silva et al.

Determination of γ_m according to Gabeler:

$$f_{y,m} = 1.14 \cdot f_{y,nom} ,$$

$$V_{fy} = 0.07 .$$

$$\gamma_m = \frac{f_{y,nom}}{f_{yd}} = \frac{f_{y,nom}}{f_{y,m} \cdot (1 - 1.64 \cdot V_{fy})} = \frac{f_{y,nom}}{1.14 \cdot f_{y,nom} \cdot (1 - 1.64 \cdot V_{fy})} = 0.9909$$

Determination of γ_m according to JCSS:

$$f_{y,m} = \alpha \cdot f_{y,nom} \cdot e^{(-u \cdot v)} - 20$$

$$V_{fy} = 0.07$$

where: $\alpha=1.05$ for webs of hot rolled sections,
 $\alpha=1.00$ otherwise (this value is used in the followings),
 $-1.5 < u < -2$ optional value ($u=-2$ is used in the followings).

Steel grade ($f_{y,nom}$)	$f_{y,m}$ [MPa]	γ_m
S235	250.32	1.061
S275	296.33	1.048
S355	388.35	1.033
S460	509.14	1.021
S690	773.71	1.008

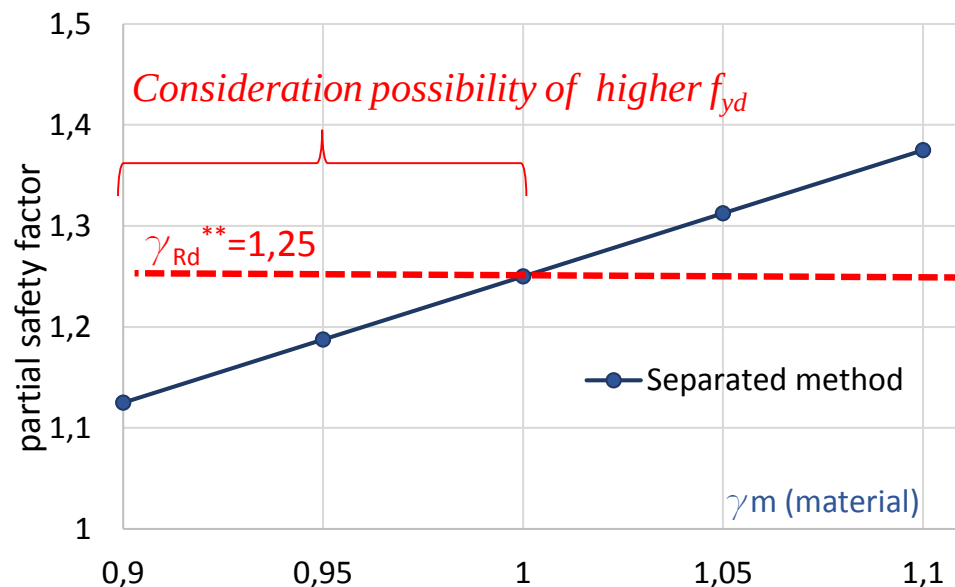
Determination of γ_m

Determination of γ_m according to L. da Silva et al.

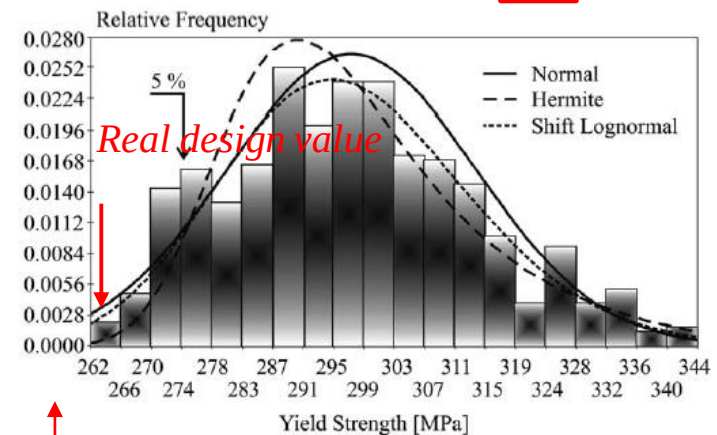
based on huge number of test results

Steel grade ($f_{y,nom}$)	n [-]	$\underline{f_{y,m}}$ [MPa]	$\underline{V_{f_y}}$	γ_m
S235	795	284.74	0.064	0.922
S275	4333	316.23	0.055	0.956
S355	1879	405.01	0.044	0.945
S460	666	474.63	0.040	1.037
S690	36	793.19	0.050	0.948

Determination of partial safety factor

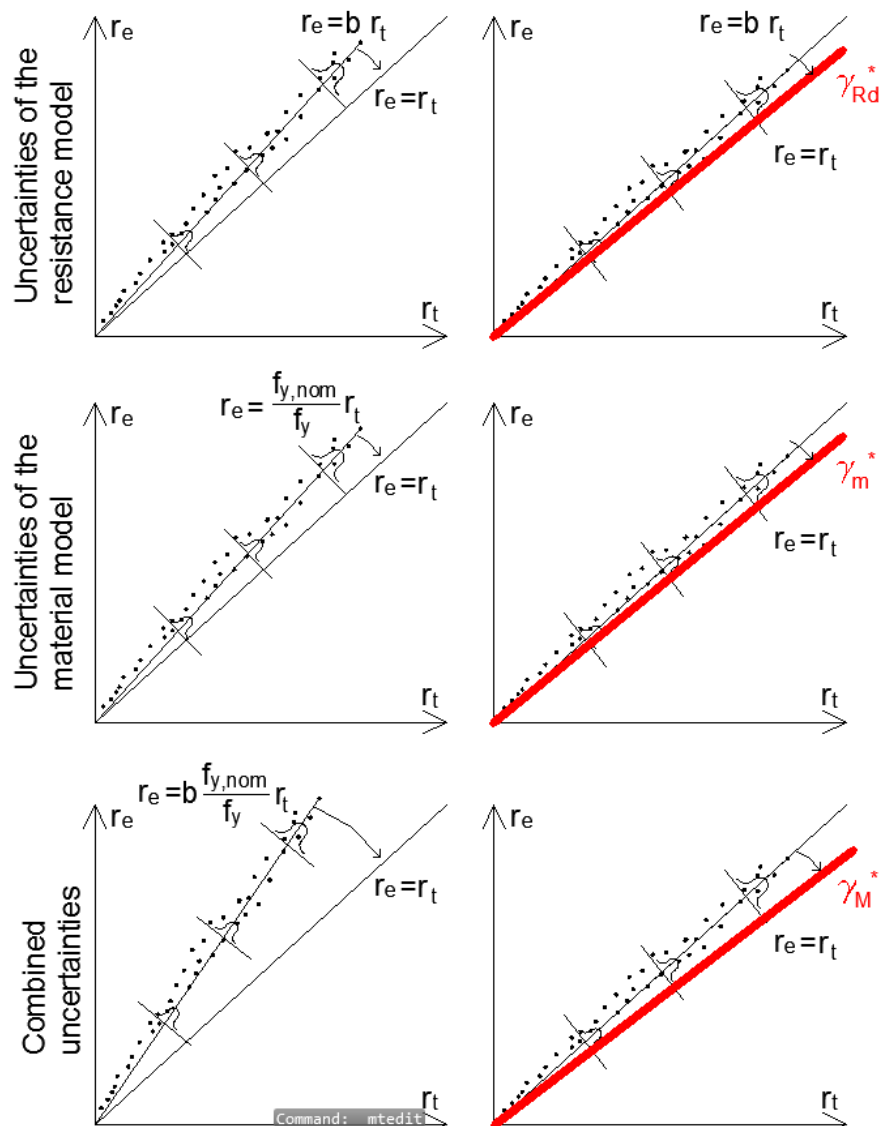


$$\gamma_{M1}^{**} = \gamma_m \cdot \gamma_{Rd}^{**}$$



S235 considered in the design method

Comparison of the evaluation methods for γ_M



$$\gamma_M^* = \frac{1}{b \cdot e^{-3.04 \cdot Q - 0.5 \cdot Q}} \cdot \frac{f_{y, nominal}}{f_{y, m} \cdot (1 - 1.64 \cdot V_{fy})}$$

$\gamma_M^* = \gamma_{Rd}^* \cdot \gamma_m^*$

$$\gamma_M^* = \frac{f_{y, nominal}}{b f_{y, m} \exp(-k_{\infty} \alpha_{rt} Q_{rt} - k_n \alpha_{\delta} Q_{\delta} - 0.5 \cdot Q^2)} \gamma_M$$

$$V_r^2 = (V_{\delta}^2 + 1) \cdot (V_{geom1}^2 + 1) \cdot (V_{geom2}^2 + 1) \cdot (V_{FEM}^2 + 1) \cdot (V_{fy}^2 + 1) - 1$$

Determination of γ_M by Johansson-Maquoi-Sedlacek

In most cases instead of a 5% fractile value R_k a value R_{nom} with nominal values for the input parameters is used as characteristic value. To consider R_{nom} instead of R_k a modified partial safety factor γ_M^* is used from:

$$\gamma_M^* = \Delta k \gamma_M$$

$$\Delta k = \frac{\exp(-2.0\sigma_{fy} - 0.5\sigma_{fy}^2)}{b \exp(-1.64\sigma_R - 0.5\sigma_R^2)}$$

$$\Delta k = \frac{0.867}{b \exp(-1.64\sigma_R - 0.5\sigma_R^2)}$$

$$\gamma_M = \frac{R_k}{R_d}$$

$$R_k = \bar{b} m_R \exp(-1.64\sigma_R - 0.5\sigma_R^2)$$

$$R_d = \bar{b} m_R \exp(\alpha_R \beta \sigma_R - 0.5\sigma_R^2)$$

where $\alpha_R \beta = -0.8 \cdot 3.8 = -3.04$

$$\gamma_M^* = \frac{0.867}{\bar{b} \cdot \exp(-3.04 \cdot Q - 0.5 \cdot Q^2)}$$



Residual stress measurement and model development

Specimens for residual stress measurement

Cold-formed						
Sign	Material	WP	b	t	Producer	Performed test
CF5-120×6_V	S500	2.4	120	6	VoestA	1
CF5-130×4_V		2.2; 2.6	130	4	VoestA	1
CF5-200×5_V		2.2; 2.6	200	5	VoestA	1
CF7-150×8_R	S700	2.4	150	8	Ruukki	1
CF7-150×4_V		2.2; 2.6	150	4	VoestA	1
CF9-120×6_R	S960	2.4	120	6	Ruukki	1+1
CF9-150×7_R		2.4	150	7,1	Ruukki	1+1*
CF9-120×4_R		2.2; 2.6	120	4	Ruukki	1

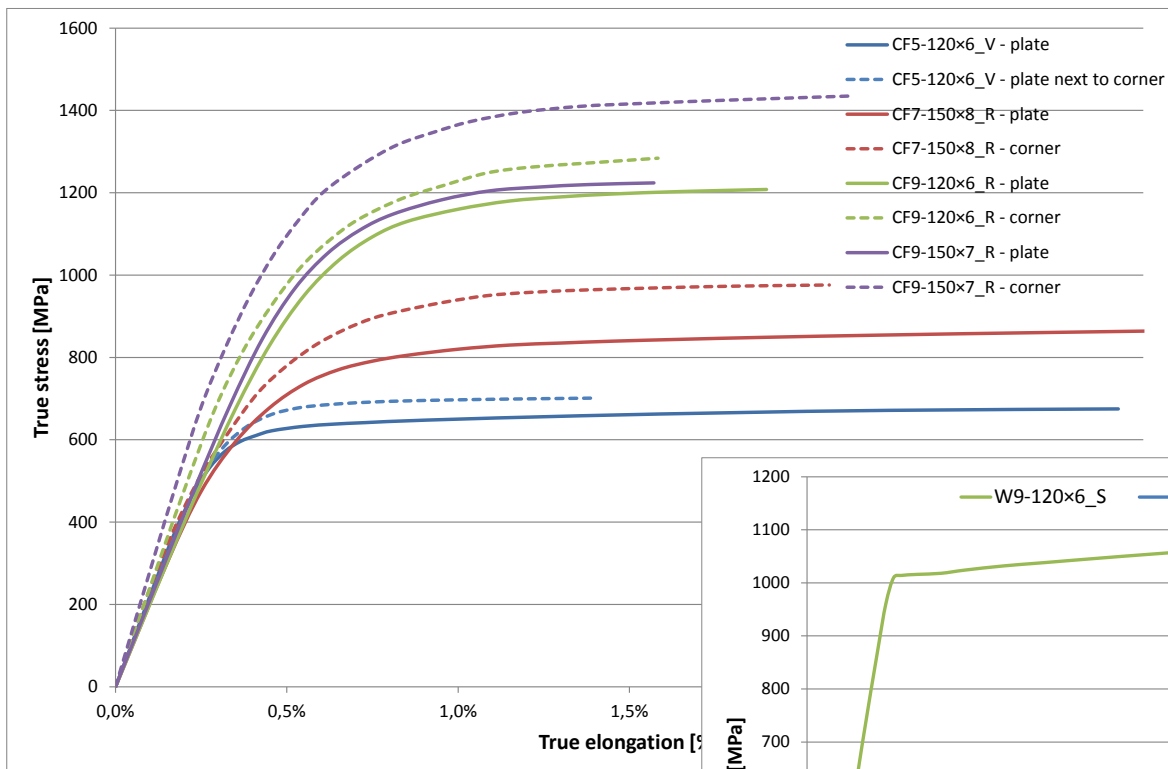
Welded						
Sign	Material	WP	b	t	Producer	Performed test
W5-120×6_R	S500	2.4	120	6	Ruukki	1
W5-150×6_R		2.4	150	6	Ruukki	1
W5-195×6_R		2.2; 2.6	195	6	Ruukki	1
W5-250×4_S		2.2; 2.6	250	4	SSAB	1
W9-120×6_S	S960	2.4	120	6	SSAB	1
W9-120×6_R		2.2; 2.6	120	6	Ruukki	1
W9-170×6_R		2.2; 2.6	170	6	Ruukki	1
W9-220×6_R		2.2; 2.6	220	6	Ruukki	1
W9-250×6_R		2.2; 2.6	250	6	Ruukki	1

What was done

- ✓ – 18 tests (10 from WP 2.2, 2.6 and 8 from WP 2.4) with cutting method
- ✓ – 1 test series with laser interferometry technique (*)
- ✓ – Three different producer (Ruukki – SSAB – Voest)

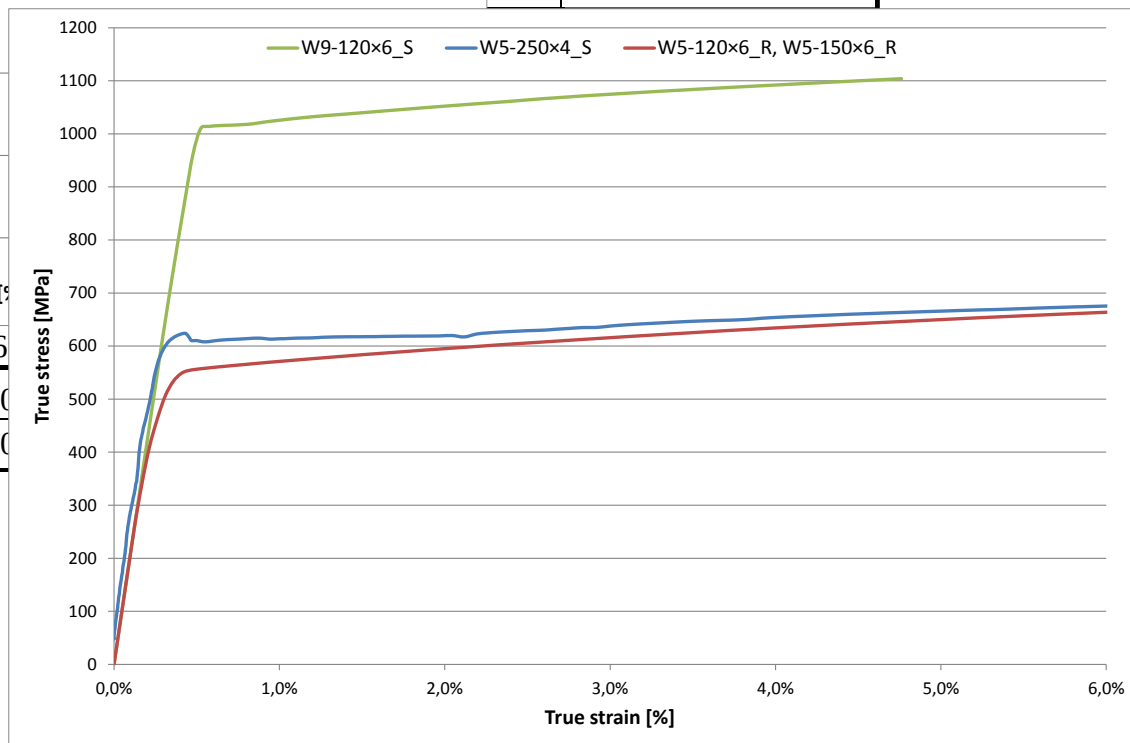


Material properties



W5-250×4_S	SSAB	624	6
W9-120×6_S	SSAB	1010	10
W9-120×6_R	Ruukki	992	10

Dia-gram	Data measured by
1	BME (4 coupon tests)
-	Voest (RWTH)
-	Voest (RWTH)
-	Voest (RWTH)
1	Ruukki



Testing method

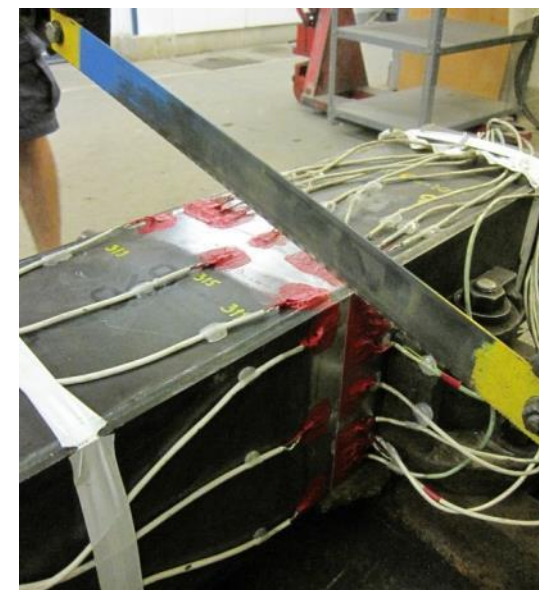
Measurement on high strength steel hollow sections on outer and inner surface using the sectioning method:

– Step 1: Preparation

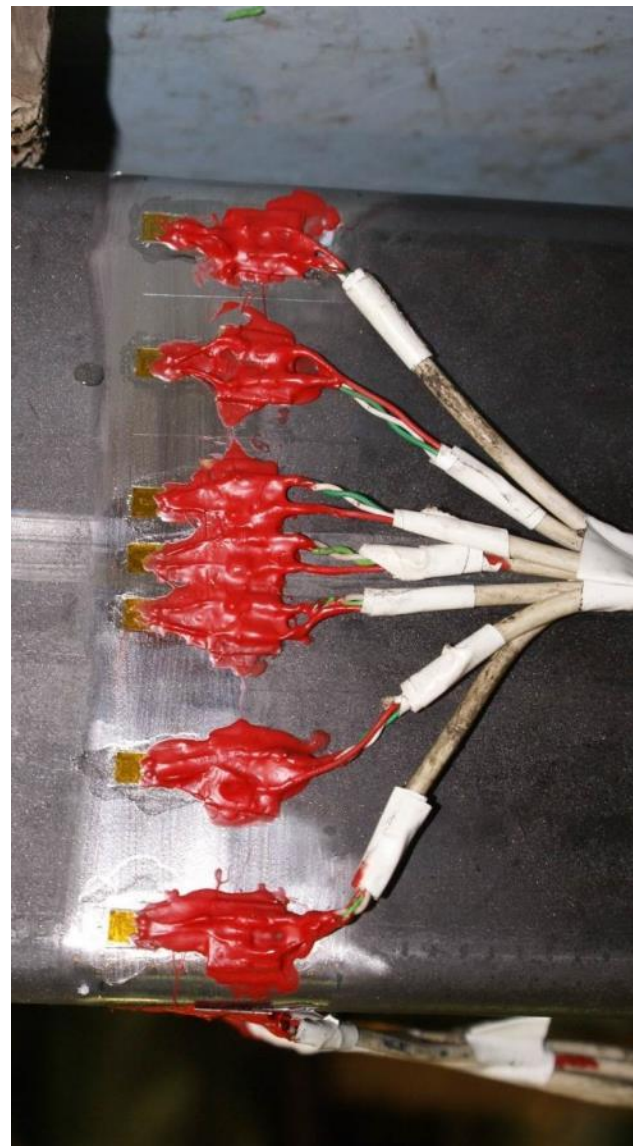
- Placing strain gauges on outer and inner surface
- Creating protection for the strain gauges against water and mechanical impact

– Step 2: Cutting

- Cutting the specimen into two pieces (transversal cutting)
- Longitudinal cuttings on both sides of gauges
- During cuttings cooling is needed by water
- During cuttings the data is recorded continuously



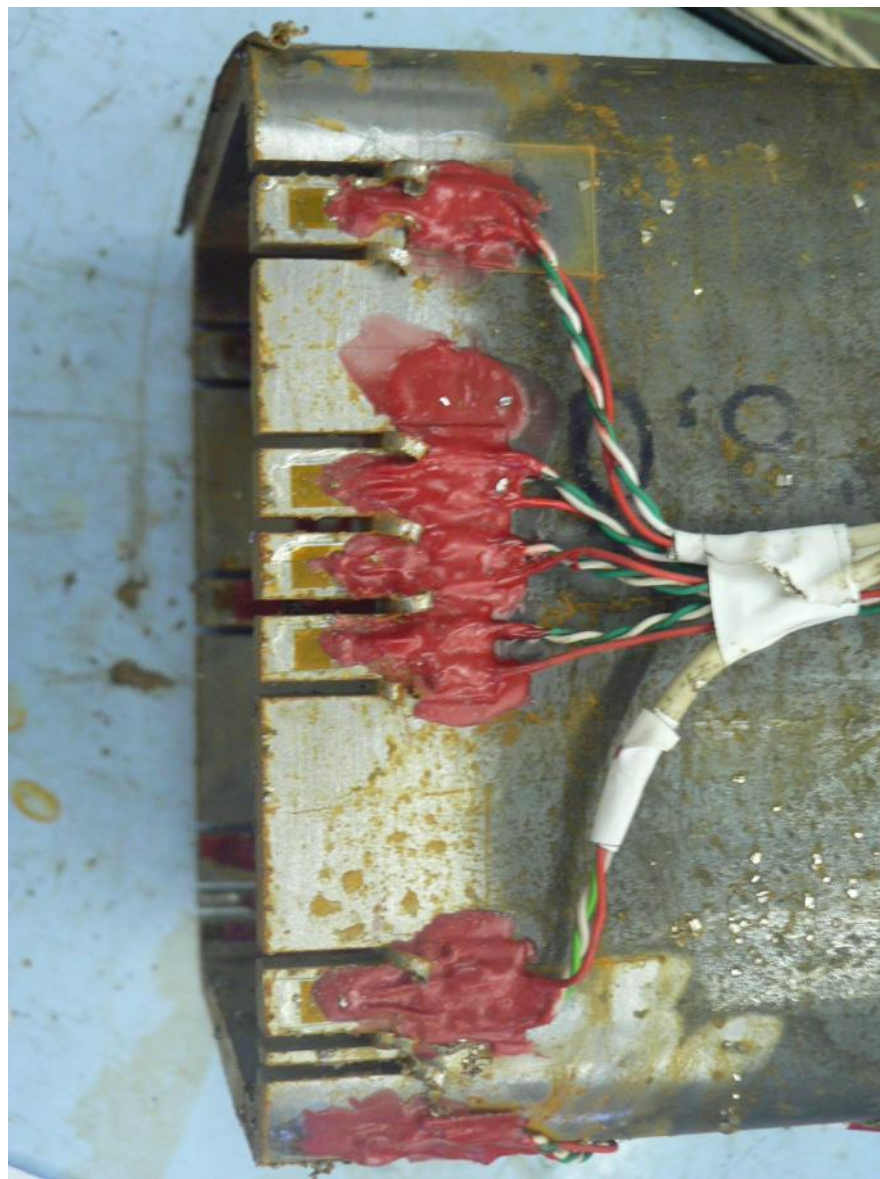
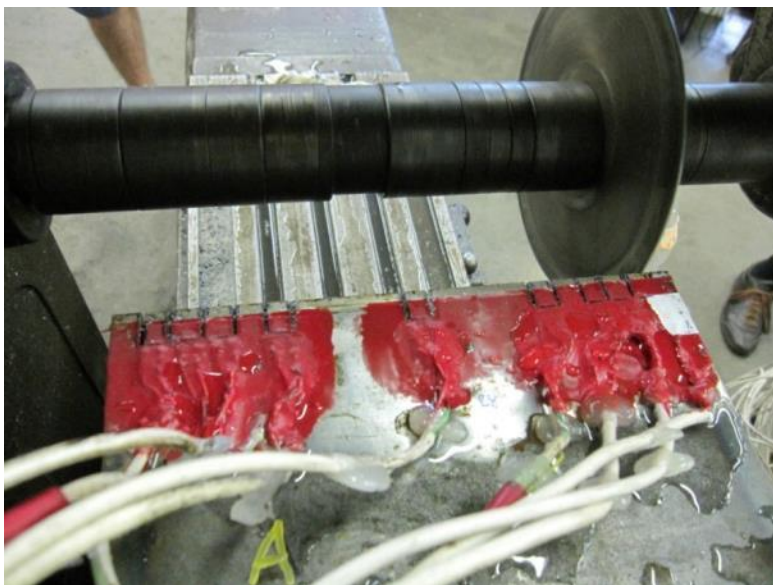
Preparation



Transversal cutting



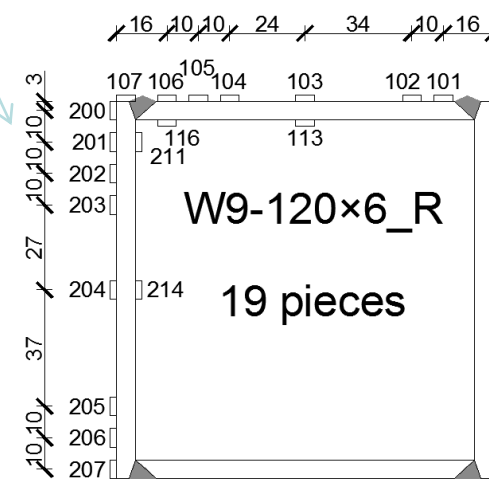
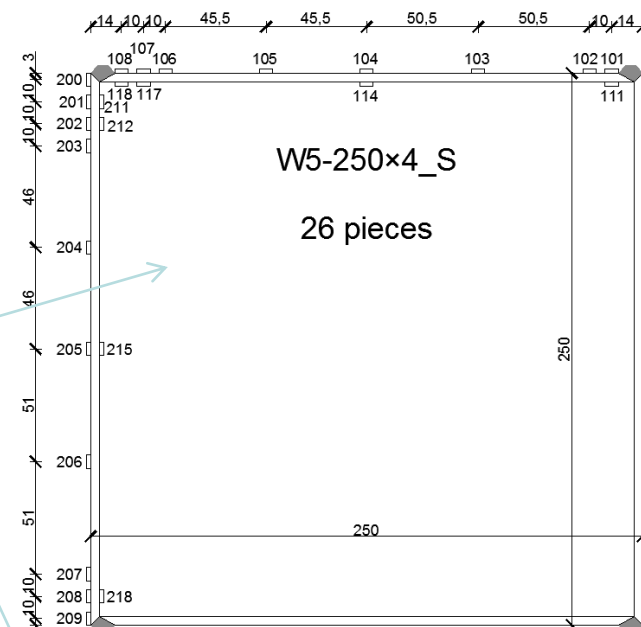
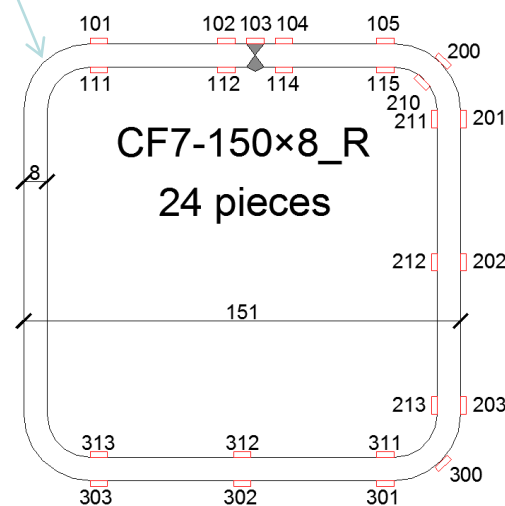
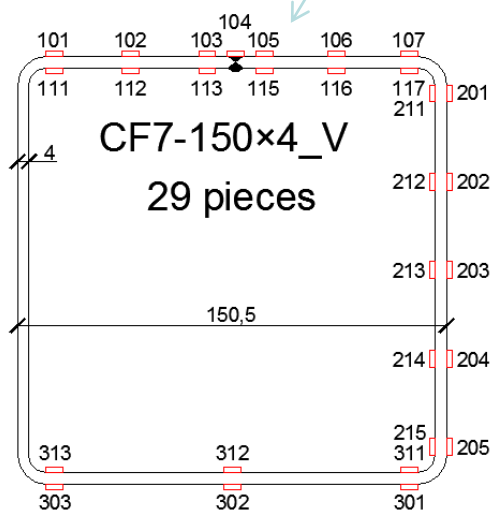
Longitudinal cutting



Strain gauges

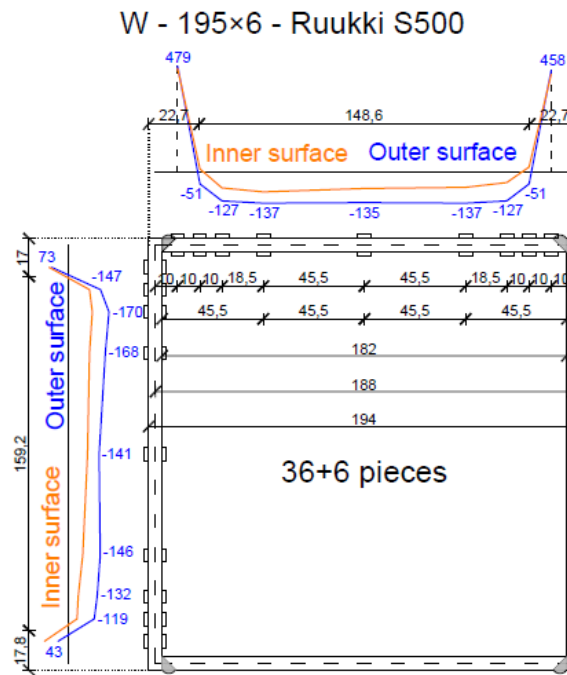
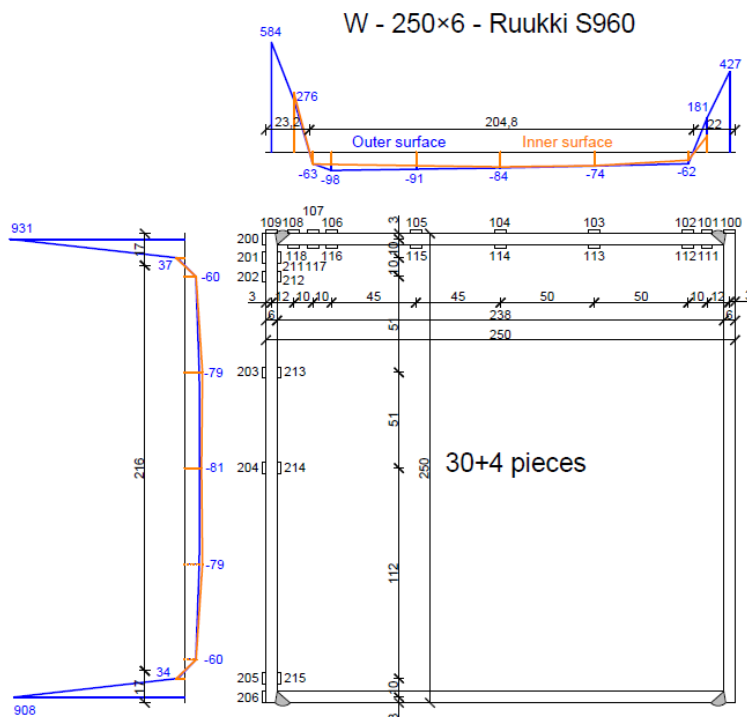
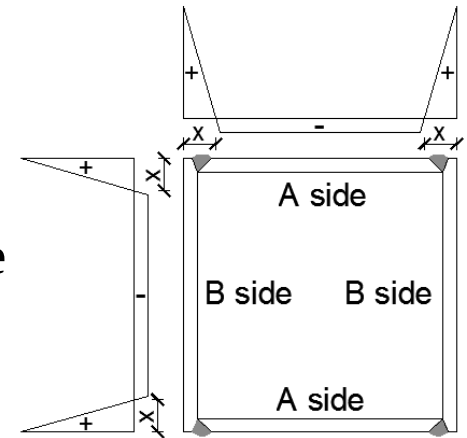
Cold-formed			
Specimen	Material	Producer	Number of strain gauges
CF5-120×6_V	S500	VoestA	17
CF5-130×4_V		VoestA	19
CF5-200×5_V		VoestA	29
CF7-150×8_R	S700	Ruukki	24
CF7-150×4_V		VoestA	29
CF9-120×6_R	S960	Ruukki	20
CF9-120×4_R		Ruukki	21
CF9-150×7_R		Ruukki	31
		Sum:	190

Welded			
Specimen	Material	Producer	Number of strain gauges
W5-195×6_R	S500	Ruukki	36
W5-150×6_R		Ruukki	20
W5-120×6_R		Ruukki	18
W5-250×4_S		SSAB	26
W9-250×6_R	S960	Ruukki	30
W9-220×6_R		Ruukki	32
W9-170×6_R		Ruukki	28
W9-120×6_R		Ruukki	19
W9-120×6_S		SSAB	18
		Sum:	227



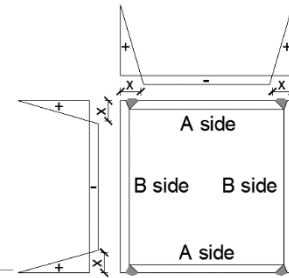
Results of the welded specimens

- Tensile residual stress at the corners, compression residual stress on the middle of the sides
- Results of inner and outer side are close to each other → for further evaluation the results of the opposite gauges are averaged

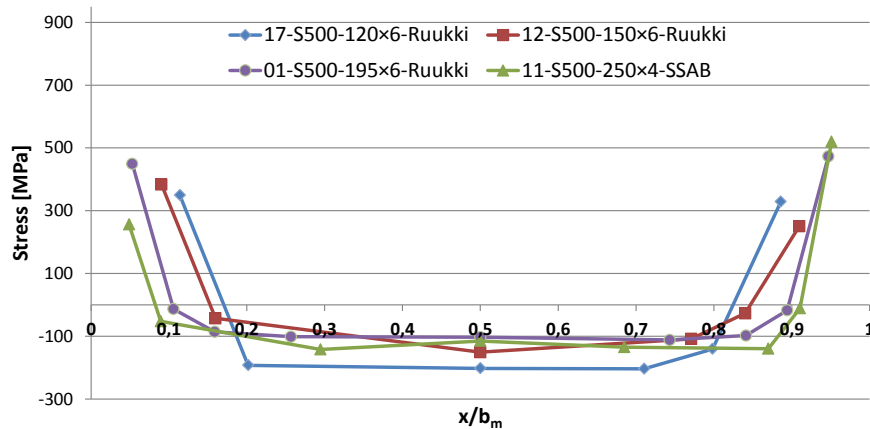


Results of the welded specimens

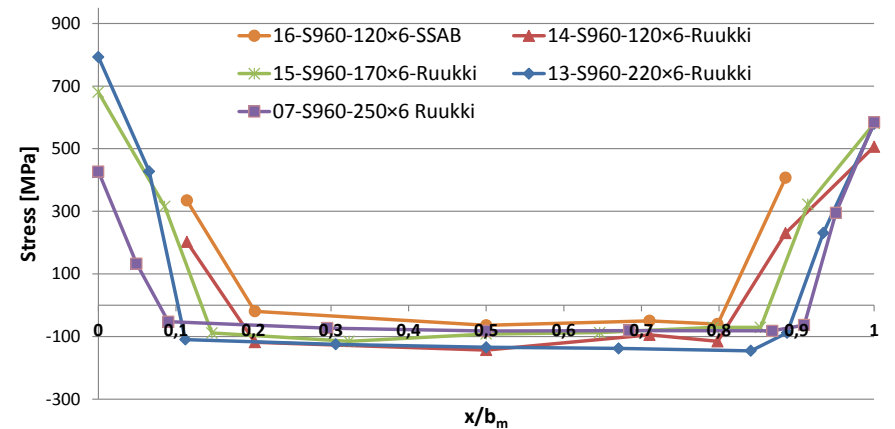
- Tensile stress in the corners is higher but the compression stress on the middle is not higher for the S960 specimens



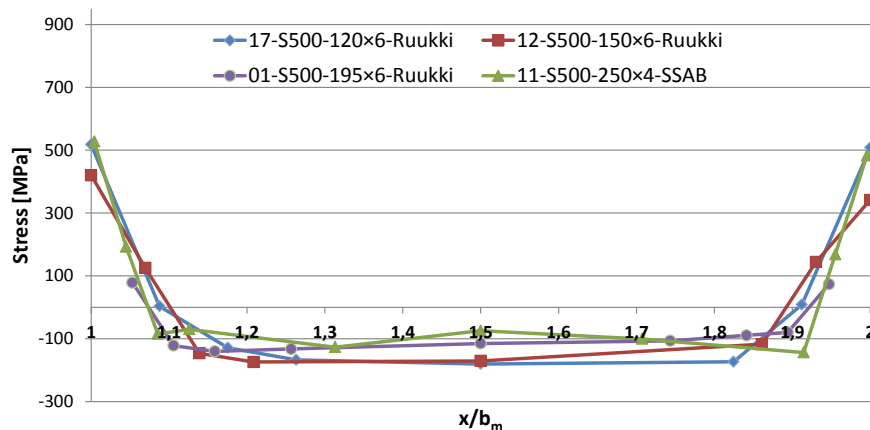
Residual stresses on the welded (A) side - S500



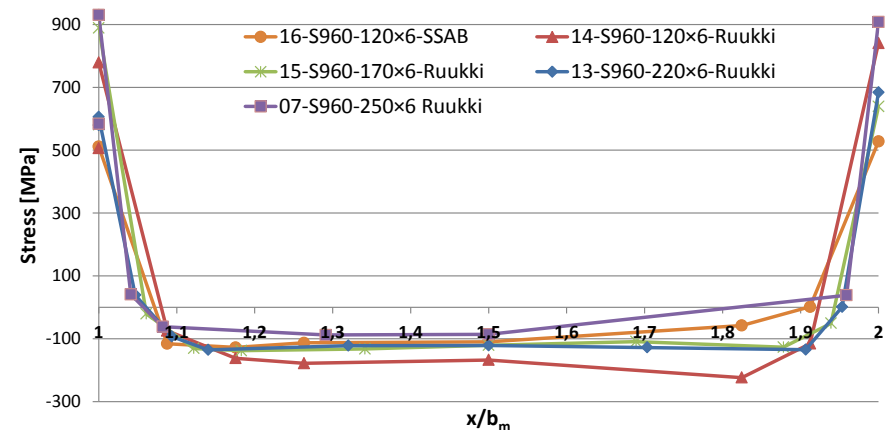
Residual stresses on the welded (A) side - S960



Residual stresses on the not welded (B) side - S500

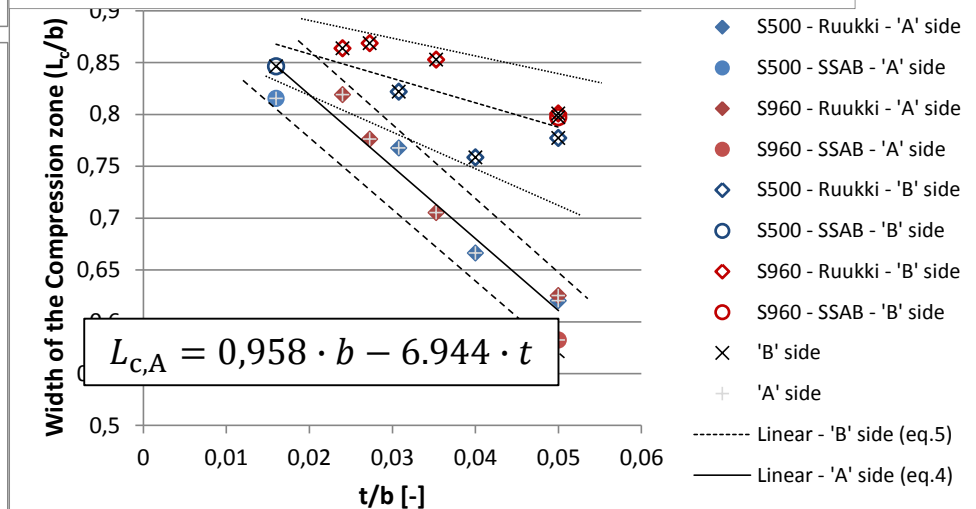
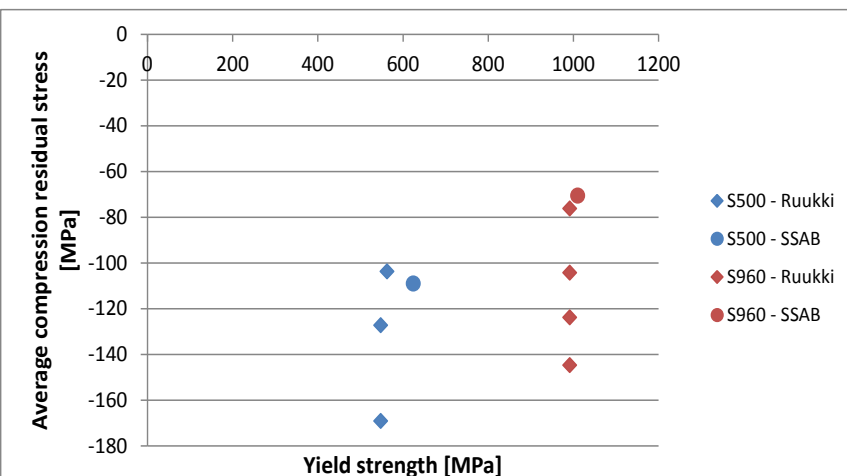
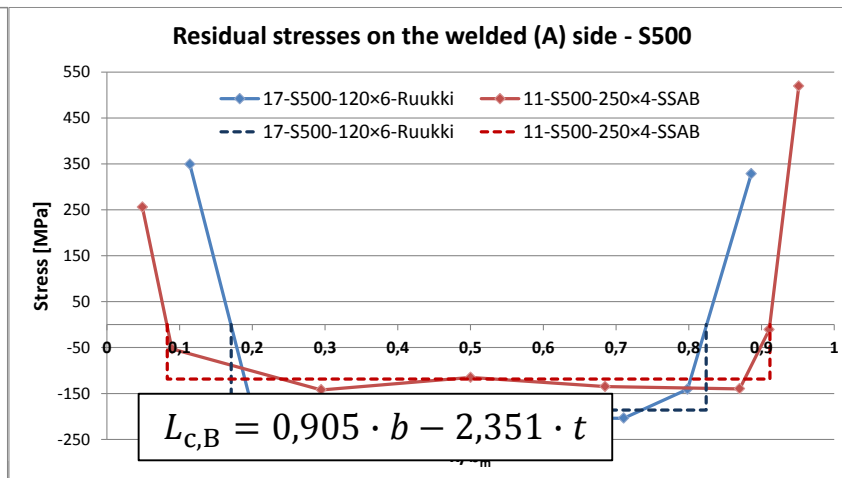
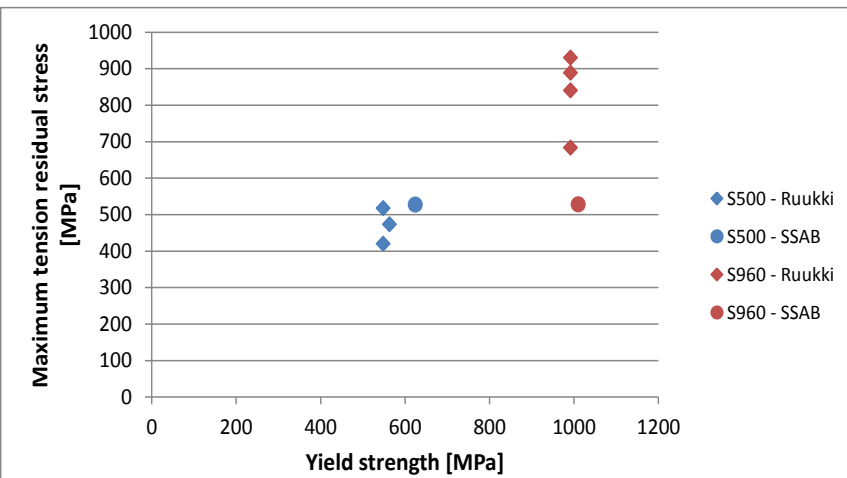
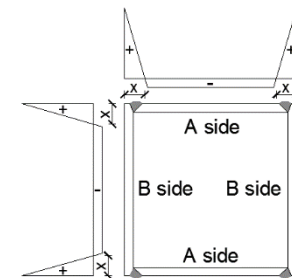


Residual stresses on the not welded (B) side - S960



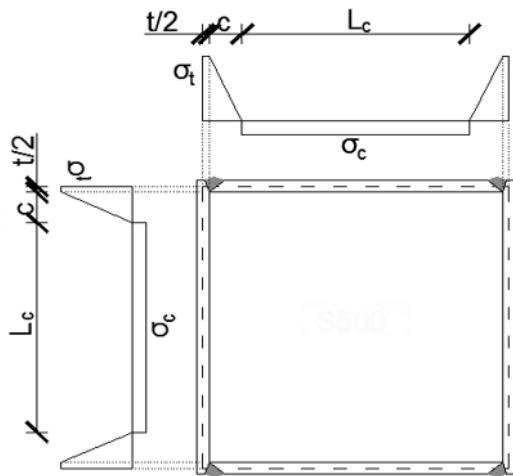
Results of the welded specimens

- The width of the compression zone and the average stress of the compression zone is calculated for every specimen



Residual stress on welded specimens

based on own and previous test results



Important findings:

1. the maximum tension residual stresses normalized by the actual yield strength do not depend on the steel grade,
2. the maximum tension residual stress depends on the plate width and the actual yield strength,
3. compression zone can be approximated by a constant stress distribution,
4. the average compression residual stress is independent from the material grade, but it depends on the b_0/t ratio and the plate thickness (t).

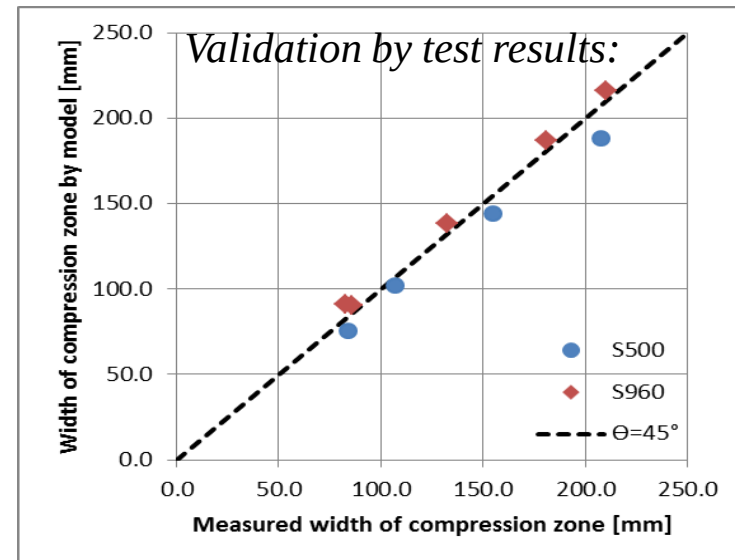
Proposed general calculation method of RS:

Tension RS: $\sigma_{rt} = \text{Min}((1.132 - 0.033 \cdot t) \cdot f_y; f_y)$

Compression RS:

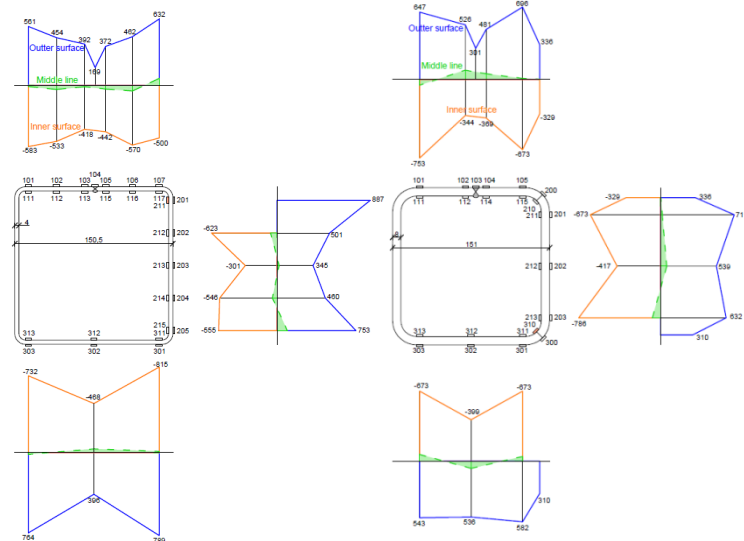
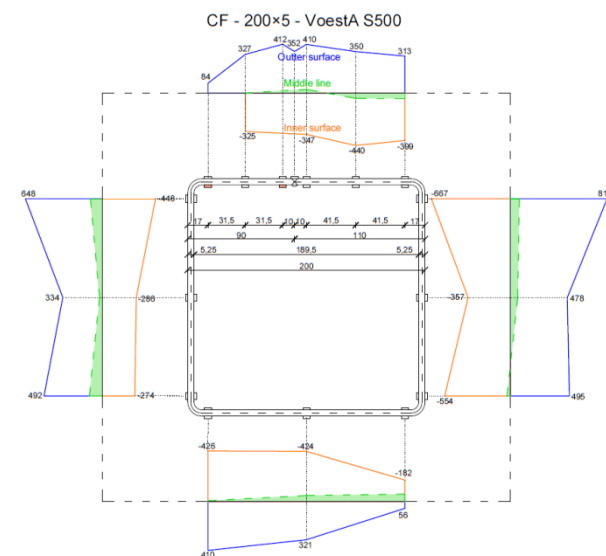
$$\text{If } t \leq 6: \sigma_{rc} = 20 - 5t - \left(14000 \cdot \frac{1}{t-2} - 800\right) \cdot \left(\frac{b_0}{t}\right)^{-1}$$

$$6: \sigma_{rc} = 20 - 5t - (4620 - 320t) \cdot \left(\frac{b_0}{t}\right)^{-1}$$



Results of the cold-formed specimens

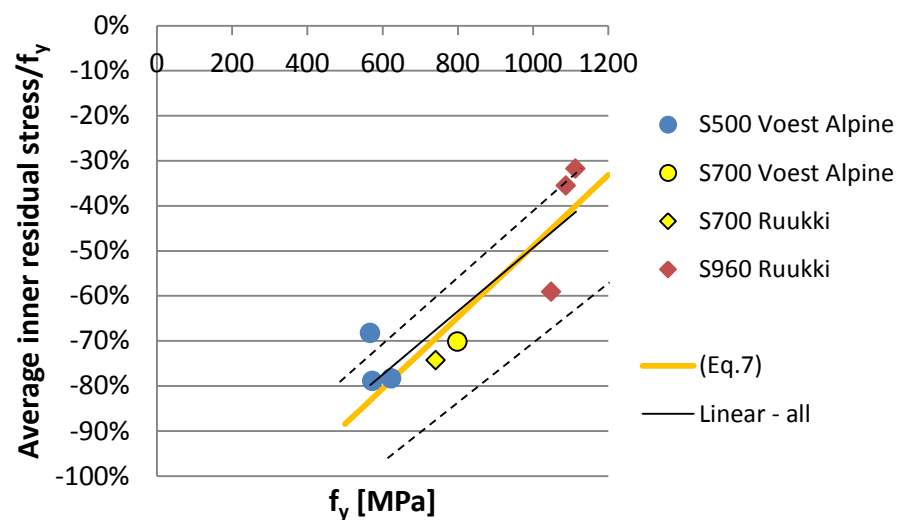
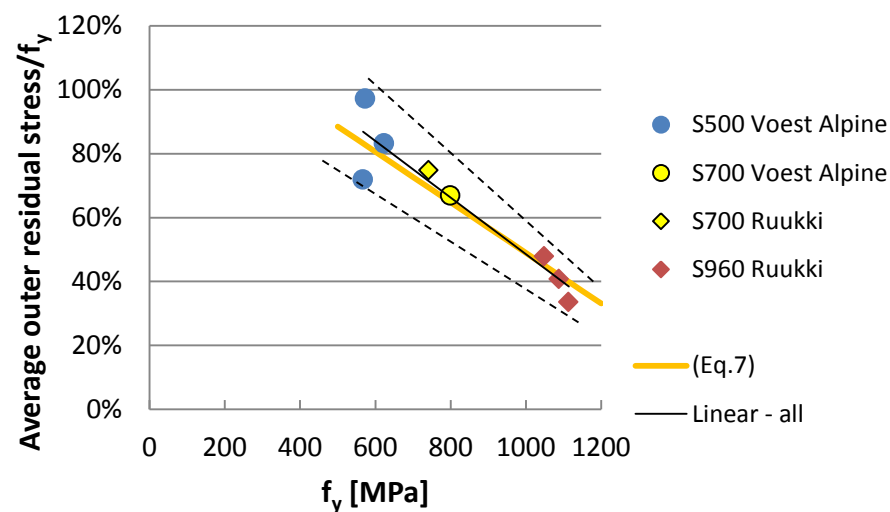
- Tensile residual stress on the outer side
- Compression residual stress on the inner side
- Membrane residual stress is negligible.
- The welding has no serious impact on the residual stress of the cold-formed specimens



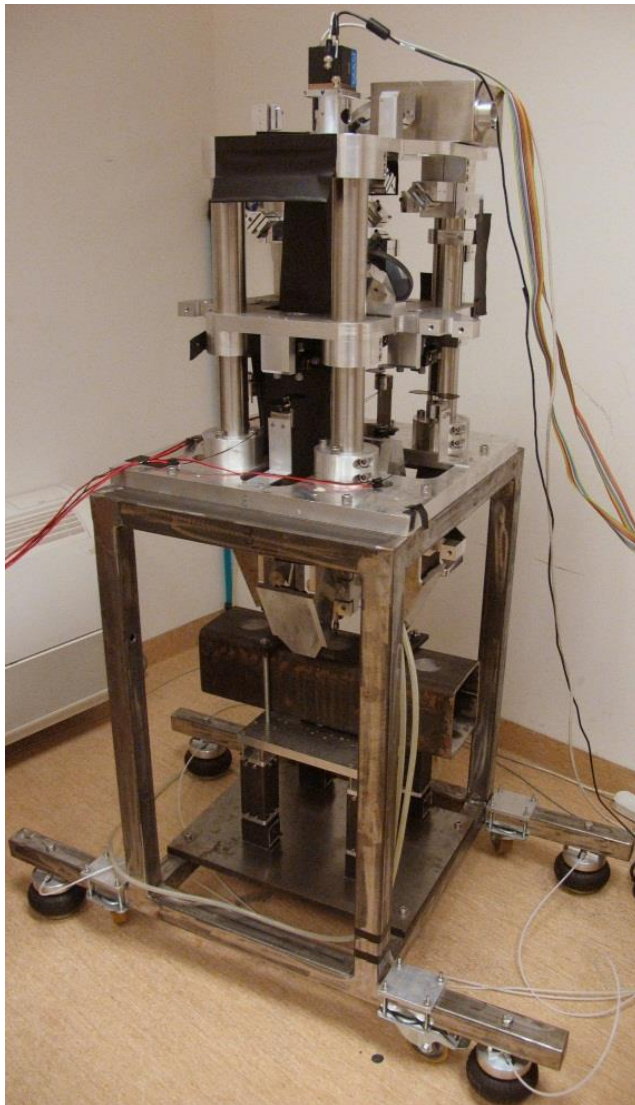
Results of the cold-formed specimens

- The average stress on the outer and on the inner surface is calculated for every specimen based on the integral of the residual stress curve
- The normalized residual stresses are evaluated
- A new formula is proposed for the average residual stress value on the surfaces:

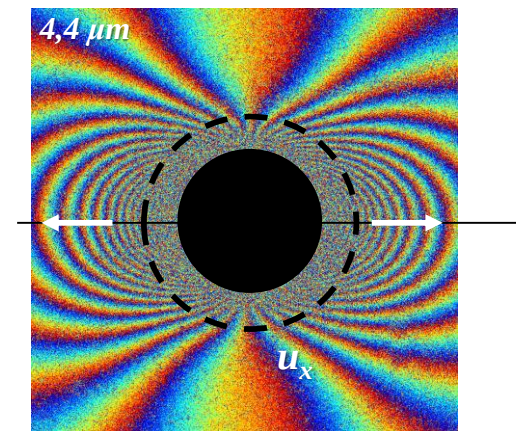
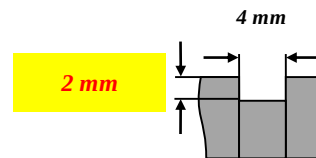
$$\sigma_{rb} = \pm \left(1,28 \cdot f_y - \frac{f_y^2}{1265 \text{ MPa}} \right),$$



Alternative residual stress measurement method



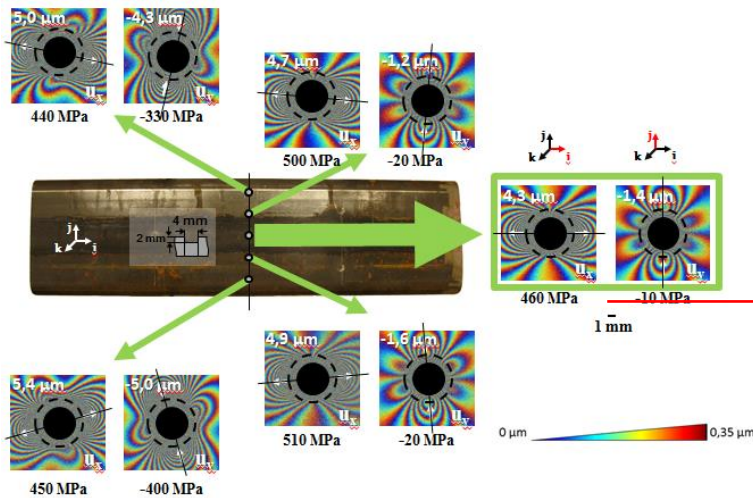
- Using „LASER-Falcon-eye” holographic gage camera
- Measurement principle:
 - *Measurement of stress relief deformation occurring at diagnostic blind (or thorough) hole drilling*
 - *Conversion of measured deformation into mechanical stress values*
- *One cold-formed specimen is examined*



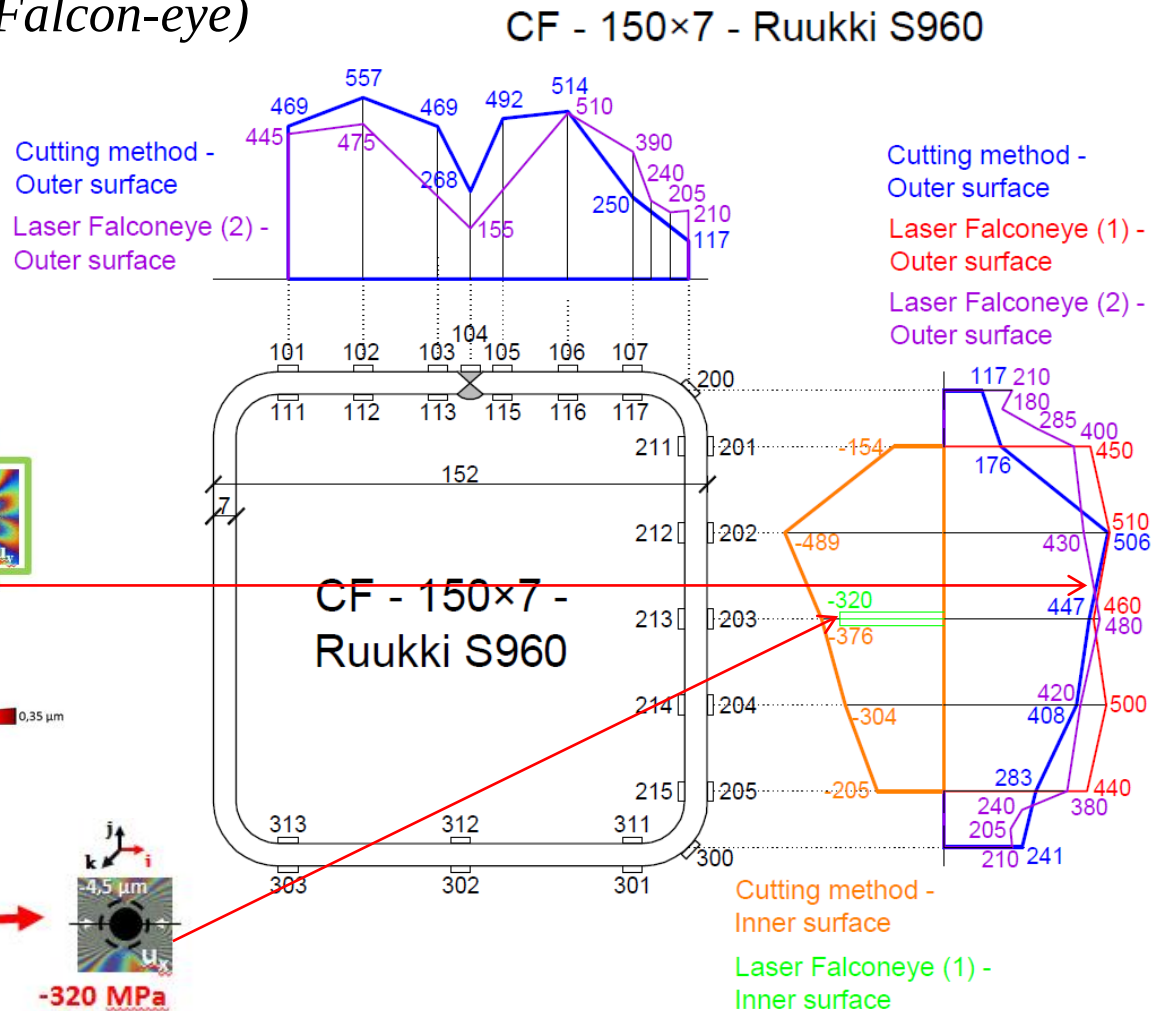
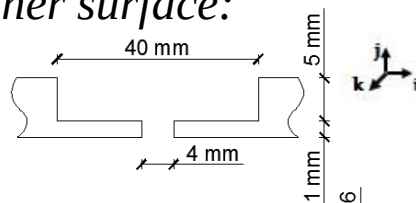
Alternative residual stress measurement method

Comparison of the sectioning method and the hole-drilling method (LASER-Falcon-eye)

Outer surface:

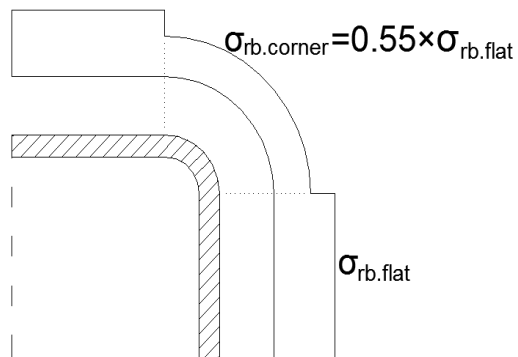


Inner surface:



Residual stress model on cold-formed specimens

based on own and previous test results



Important findings:

1. the model assumes constant stress distribution in the flat plate parts as well as in the corner zone,
2. bending residual stresses are the dominant residual stresses,
3. membrane residual stresses are close to zero,
4. average residual stresses for HSS sections are smaller than for NSS compared to the yield strength,
5. the residual stresses in the corner zone are significantly smaller than the values measured in the middle of the plates.

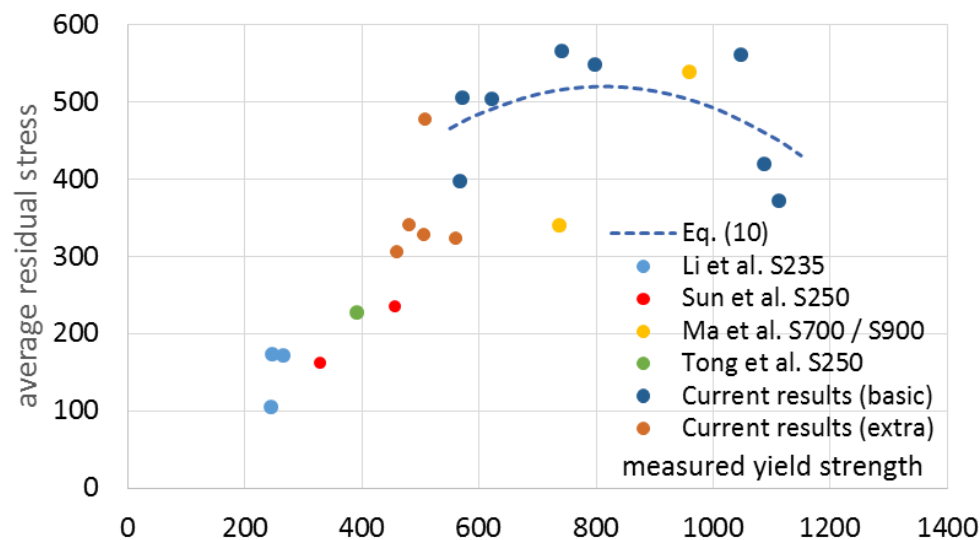
Proposed general calculation method of RS:

$$\sigma_{rb,flat} = \pm \left(1.28 - \frac{f_y}{1270 \text{ MPa}} \right) \cdot f_y$$

$$\sigma_{rb,corner} = \pm 0.55 \cdot \sigma_{rb,flat},$$

Application limitations:

- applicable for specimens produced by the “continuous forming” manufacturing method,
- HSS (S500 – S960) square hollow sections





***Experimental flexural buckling tests
and
buckling curve development***

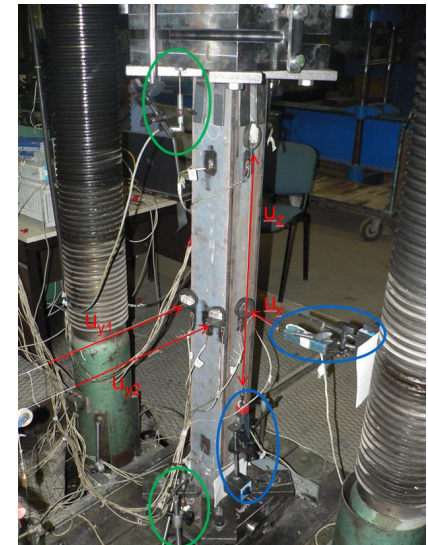
Specimens for global buckling tests

Cold-formed specimens							
L_{eff}	b	t	material	producer	λ_{gl}	in Bp	Done
2945	120	6,1	S500	VoestA	1,10	3	3
2640	140	8	S500	Ruukki	0,86	1	1
1940	140	8	S500	Ruukki	0,63	1	1
2940	120	6	S700	Ruukki	1,21	2	2
2940	150	8	S700	Ruukki	0,96	2	2
2140	150	8	S700	Ruukki	0,71	2	2
2938	120	6	S960	Ruukki	1,45	2	2
2940	150	7	S960	Ruukki	1,17	2	2
1840	150	7	S960	Ruukki	0,73	2	2

Welded specimens							
L_{eff}	b	t	material	producer	λ_{gl}	in Bp	Done
2940	120	6	S500	Ruukki	1,03	1	1
2440	120	6	S500	Ruukki	0,86	1	1
2140	150	6	S500	Ruukki	0,60	1	1
2940	140	6	S700	SSAB	0,97	1	1
1640	140	6	S700	SSAB	0,54	1	1
2940	180	8	S700	Ruukki	0,79	1	1
2940	120	6	S960	SSAB	1,44	1	1
1340	120	6	S960	SSAB	0,65	1	1
2740	160	8	S960	Ruukki	1,00	1	1

What was done

- ✓ – 18 types of test; **58** tests
- ✓ – **12** different types of cross-section
- ✓ – Slenderness range between **0,55** and **1,45**
- ✓ – Six different steel grades (S235 – S355 – S420/460 - S500 – S700 – S960)



Testing matrix

Type	Mat.	#	Producer	b _{nom}	t _{real}	L _{column}	L _{hinge}	E	f _y	class	λ_{gl}	χ_c	N _{b,Rd}
Cold-formed	S500	1a	VoestA	120	6,00	2806	2946	210000	623	1.	1,10	0,48	794
		1b	VoestA	120	6,05	2806	2946	210000	623	1.	1,11	0,48	800
		1c	VoestA	120	6,05	2806	2946	210000	623	1.	1,10	0,48	800
		13	Ruukki	140	8,00	2500	2640	210000	614	1.	0,86	0,63	1541
		14	Ruukki	140	8,00	1800	1940	210000	614	1.	0,63	0,77	1888
	S700	2a	Ruukki	150	7,85	2800	2940	210000	742	1.	0,96	0,56	1788
		2b	Ruukki	150	7,75	2800	2940	210000	742	1.	0,96	0,56	1769
		15a	Ruukki	150	8,00	2000	2140	210000	751	1.	0,71	0,72	2327
		15b	Ruukki	150	8,00	2000	2140	210000	751	1.	0,71	0,72	2327
		16a	Ruukki	120	6,00	2800	2940	210000	741	1.	1,21	0,43	845
		16b	Ruukki	120	6,00	2800	2940	210000	741	1.	1,21	0,43	845
	S960	3a	Ruukki	120	5,95	2798	2938	210000	1088	2.	1,46	0,33	942
		3b	Ruukki	120	6,05	2800	2940	210000	1088	2.	1,45	0,33	949
		4a	Ruukki	150	6,90	2800	2940	210000	1114	2.	1,17	0,45	1944
		4b	Ruukki	150	6,85	2800	2940	210000	1114	2.	1,17	0,45	1938
		5a	Ruukki	150	6,90	1700	1840	210000	1114	2.	0,73	0,71	3067
		5b	Ruukki	150	6,85	1700	1840	210000	1114	3.	0,73	0,71	3055
Welded	S500	6	Ruukki	120	6,00	2800	2940	210000	558,5	1.	1,04	0,52	788
		7	Ruukki	120	6,00	2300	2440	210000	534	1.	0,84	0,63	926
		8	Ruukki	150	5,90	2000	2140	210000	556,5	2.	0,60	0,78	1505
	S700	17	SSAB	140	6,00	2800	2940	210000	670	2.	0,97	0,56	1207
		18	SSAB	140	6,00	1501	1641	210000	670	2.	0,54	0,82	1769
		9	Ruukki	180	8,05	2800	2940	210000	757	2.	0,80	0,66	2756
	S960	10	SSAB	120	6,05	2800	2940	210000	1005	2.	1,43	0,34	928
		11	SSAB	120	6,05	1200	1340	210000	1005	2.	0,65	0,76	2078
		12	Ruukki	160	8,00	2600	2740	210000	1109	3.	1,03	0,52	2827

Tests are carried out in three phase:

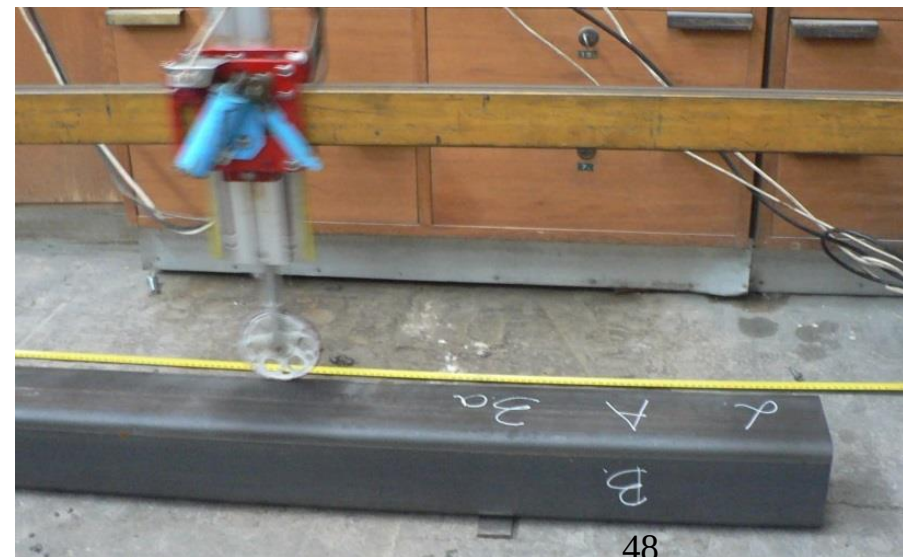
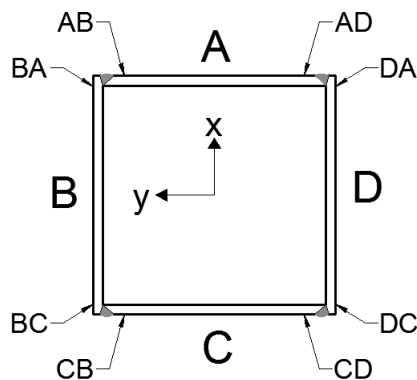
First phase (3)	2014. Aug
Second phase (15)	2015. Jan
Third phase (8)	2015. May

The specimens are grouped into four groups based on global slenderness:

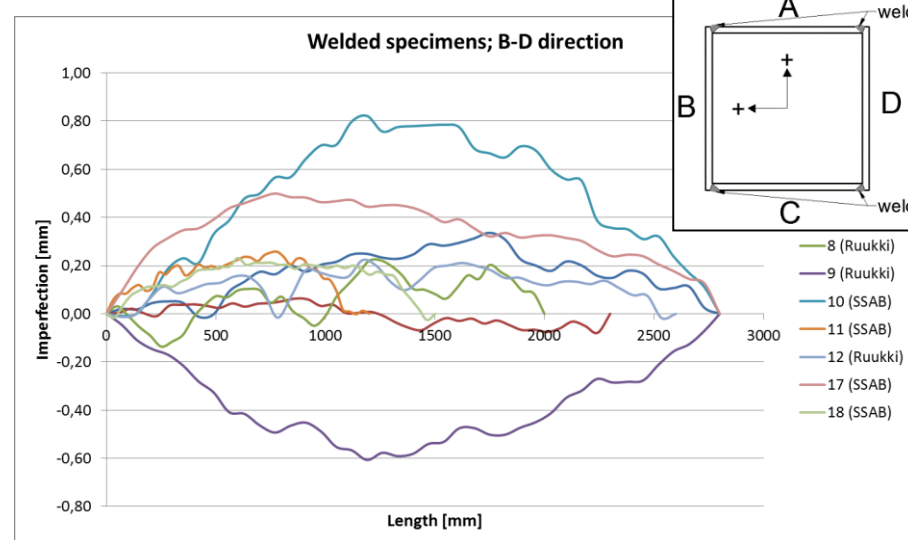
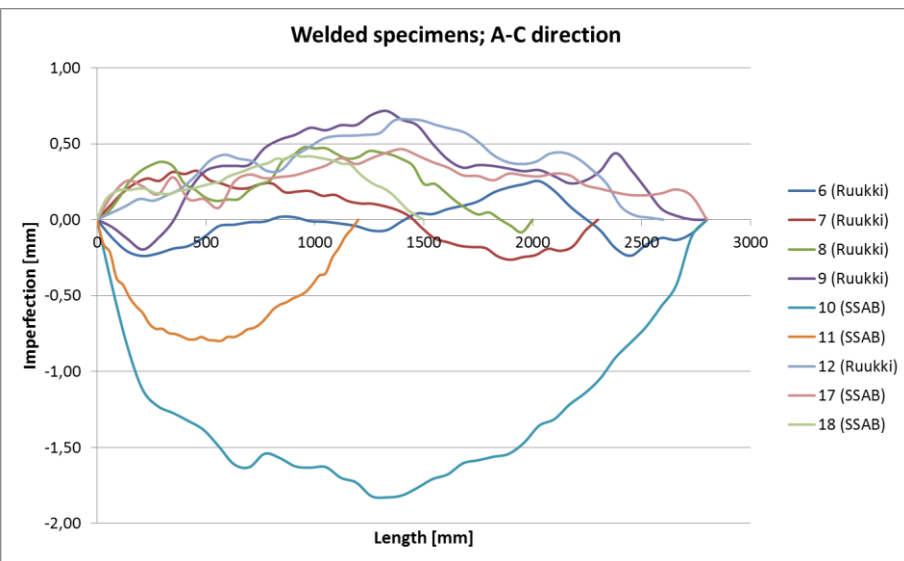
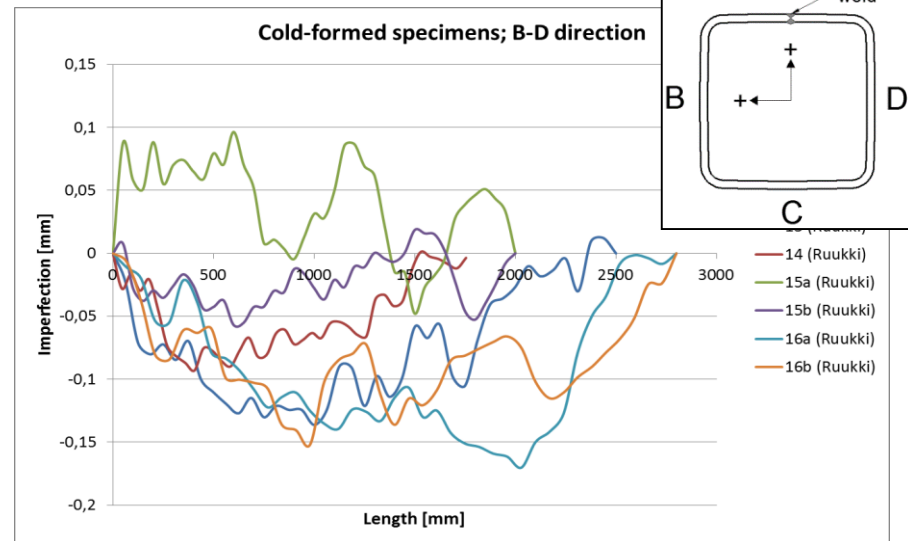
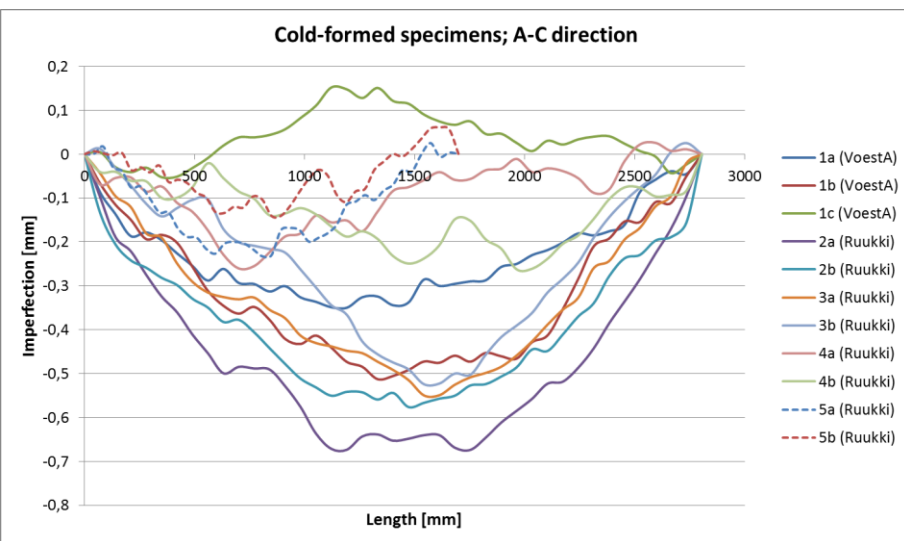
1st group	$0,54 < \lambda < 0,80$
2nd group	$0,84 < \lambda < 0,97$
3rd group	$1,03 < \lambda < 1,21$
4th group	$1,43 < \lambda < 1,46$

Out-of-straightness imperfection measurements

- Measurement using a moving inductive displacement transducer.
- On each specimen at least 8 lines (2 on each side next to the two corner) are measured four or six times
- $26 \text{ specimens} \times 4 \text{ sides} \times 2 \text{ corners} \times 2 \text{ directions} \times 2 \text{ (or 3) measurement} =$ minimum **832** continuous data line

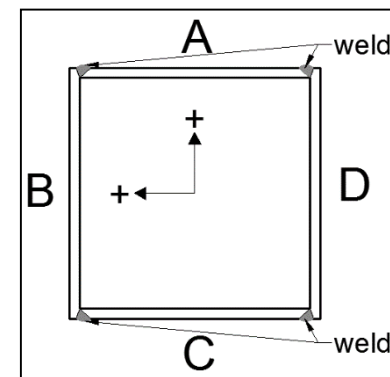
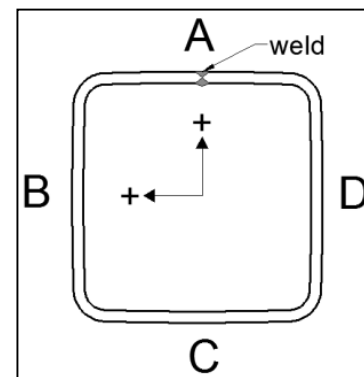
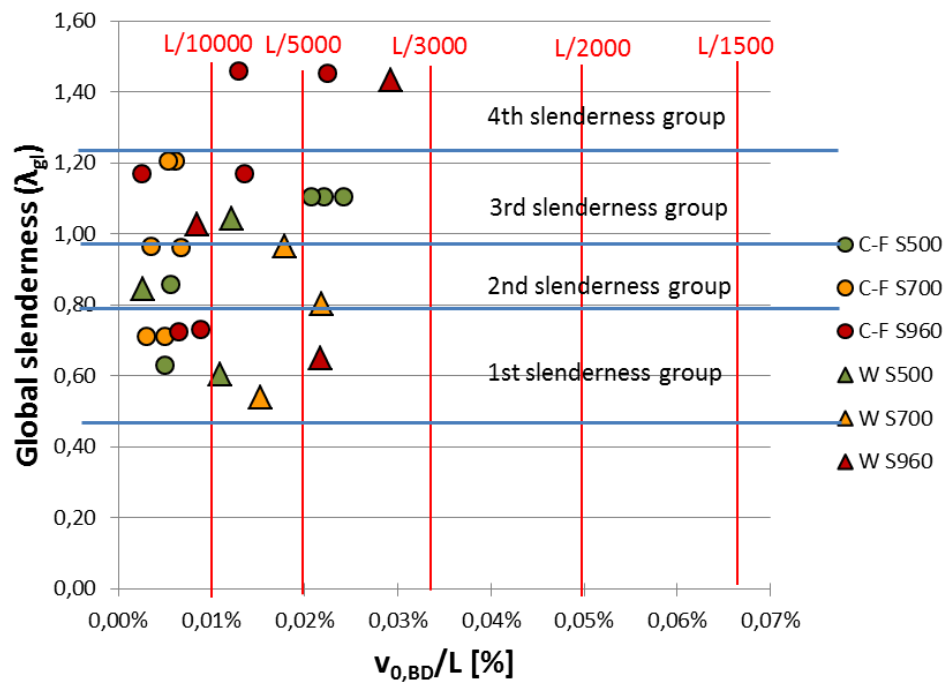
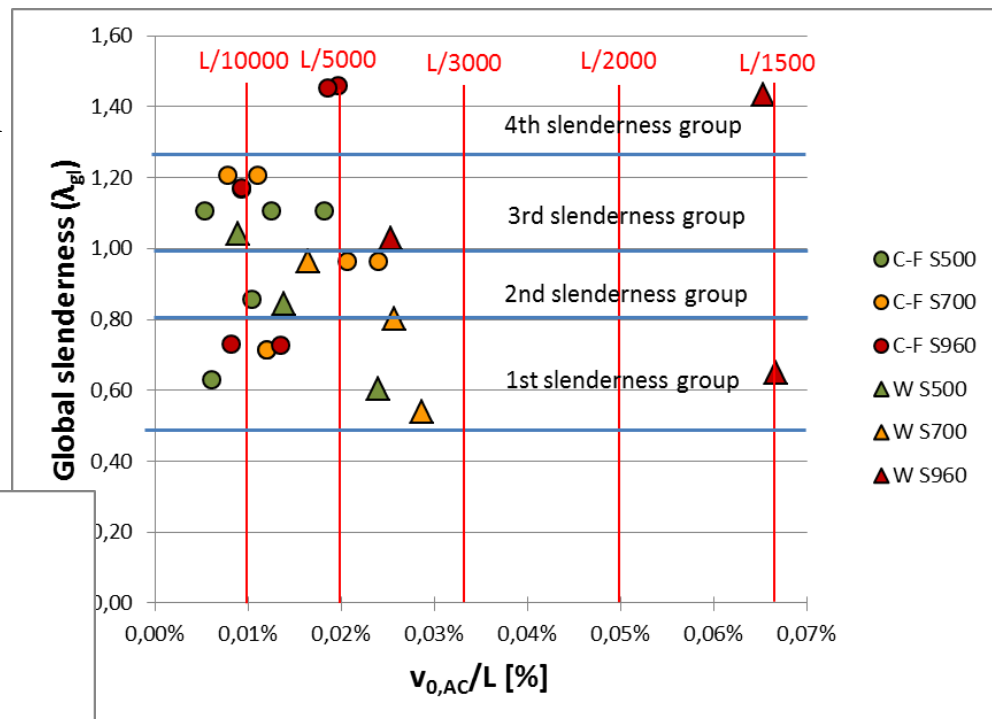


Out-of-straightness imperfection measurements

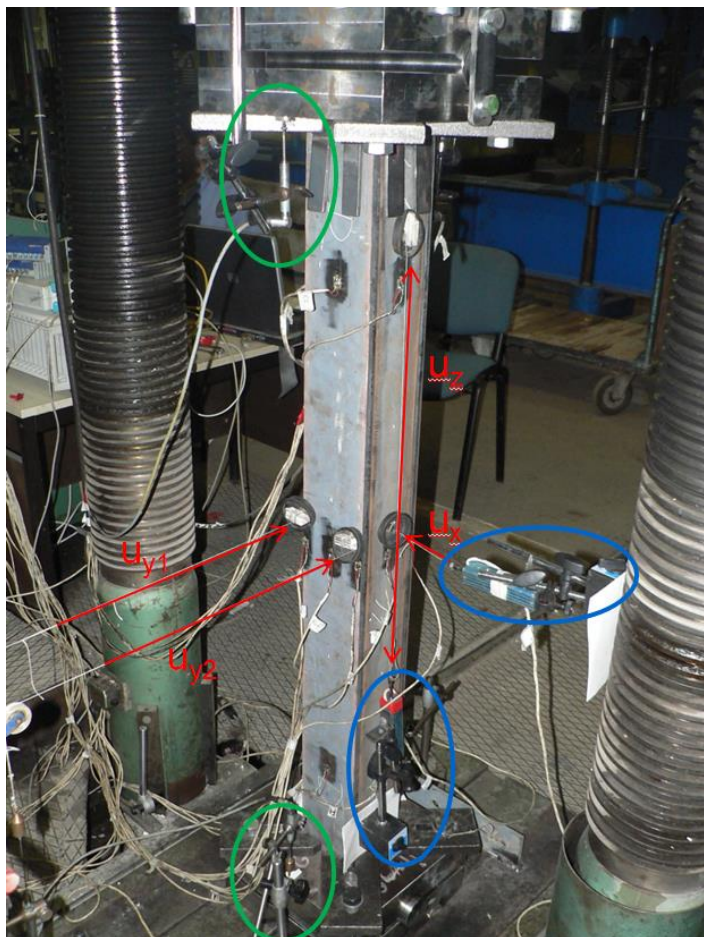


Out-of-straightness imperfection measurements

- Global imperfection shape is close to sinus in most cases.
- Amplitude is less than $L/3000$ in all cases, except two.
- The imperfection in case of SSAB S960 specimens in A-C direction is about $L/1500$.



Flexural buckling tests – Experimental program



Test matrix					
Type	Material	Number of specimens	Type	Material	Number of specimens
Welded	S500	3	Cold-formed	S420	14
	S700	3		S460	14
	S960	3		S500	5
Σ		9		S700	6
				S960	6
			Σ		45

Measured during loading:

- Force
- Axial displacement
- Lateral displacement
- Stress distribution
- Hinge rotation

Test results: Buckling load and loading diagrams for different slendernesses

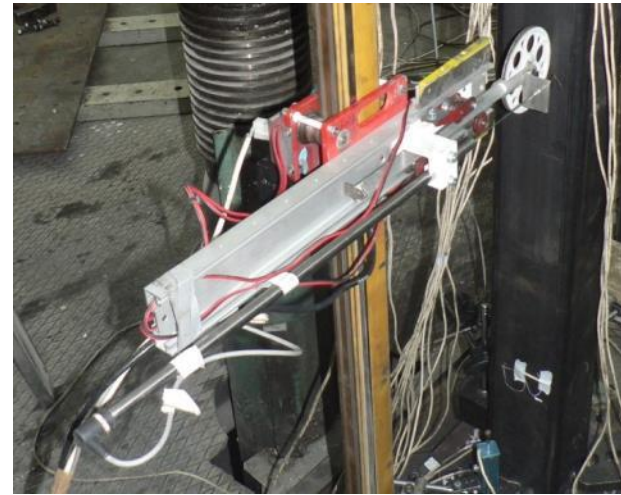


Global buckling tests - details

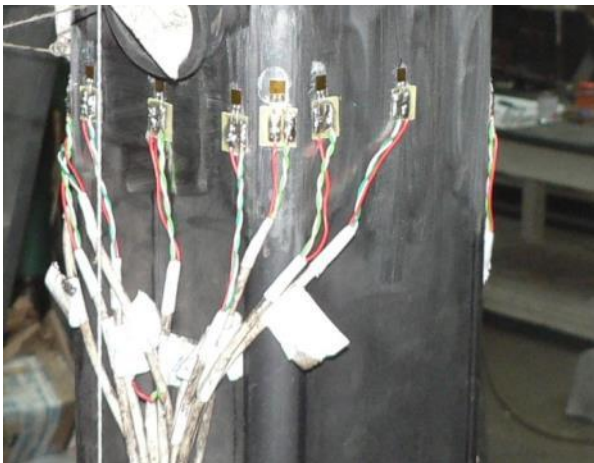
Hinged end-support:



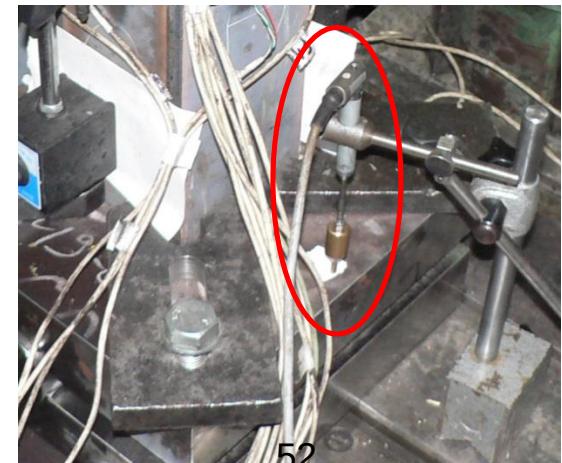
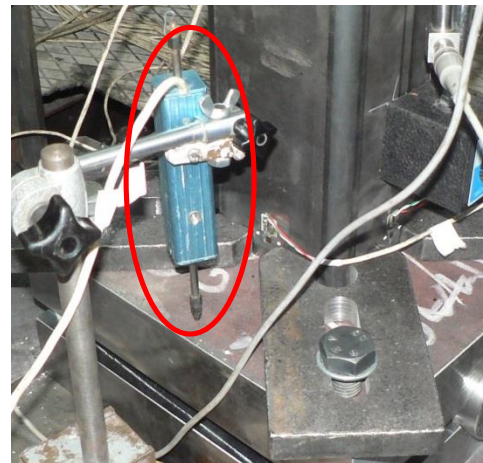
Shape-measuring equipment:



Strain gauges:

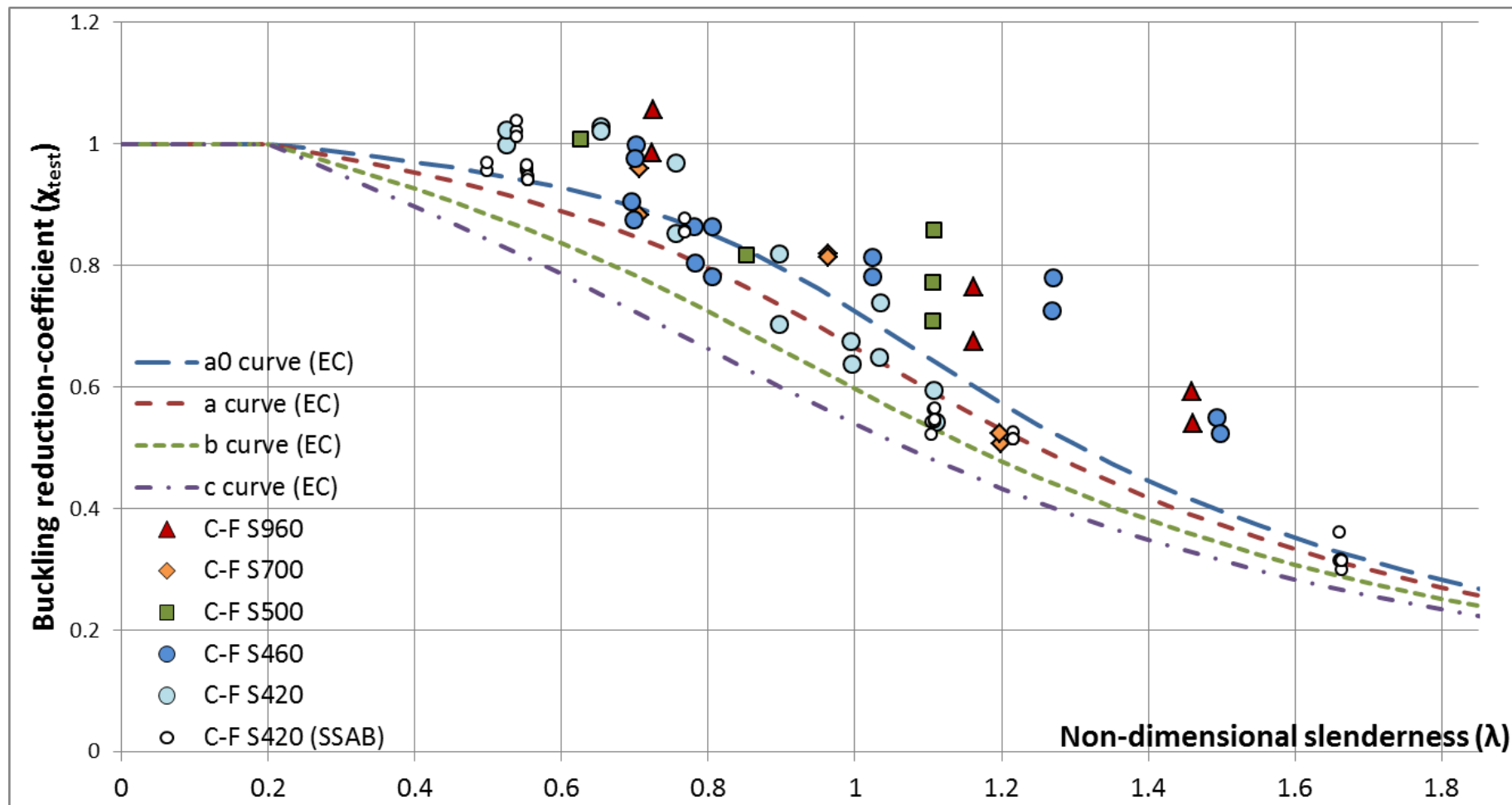


Measuring of the hinge rotation:



Flexural buckling tests on cold-formed specimens

- The buckling load is always **higher than the buckling curve b**.
- New test results are in good agreement with test results from literature.



Flexural buckling tests on cold-formed specimens

- Statistical evaluation made based on γ_{M1}^* partial safety factor

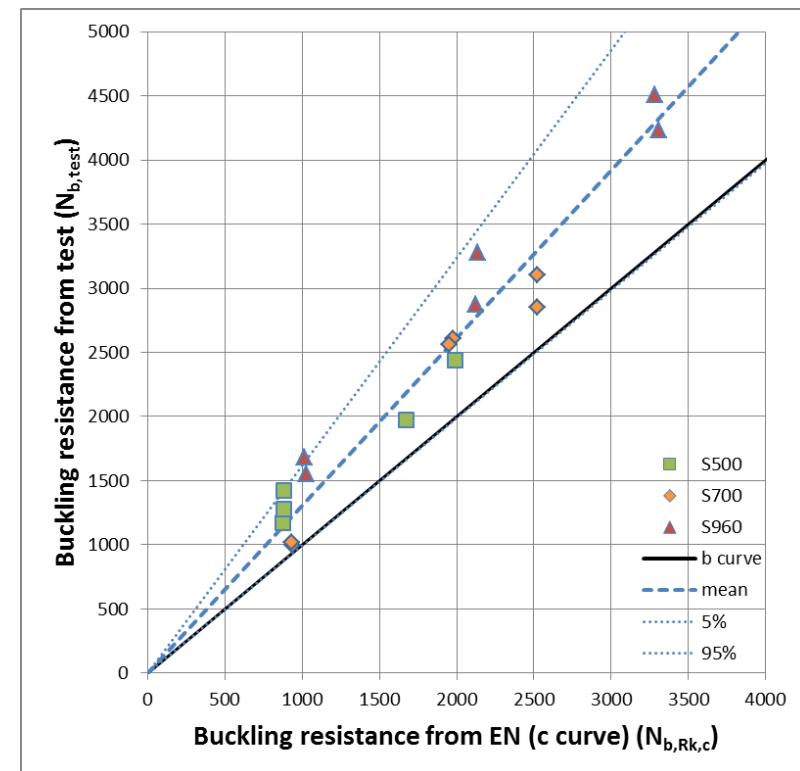
b curve							
Specimens	λ_{gl}	n	b	V_δ	$k_{5\%}$	Δk	γ_{M1}^*
S960	all	6	1.37	0.096	1.11	0.79	0.94
S500 S700 S960	all	17	1.31	0.132	0.96	0.87	1.08
	0.5-0.8	5	1.27	0.071	1.09	0.83	0.97
	0.8-1.1	3	1.28	0.062	1.12	0.81	0.94
	1.1-1.5	9	1.42	0.161	0.96	0.83	1.07
	mean of the factors for the groups:				1.06		0.99
S460	all	14	1.17	0.163	0.79	1.01	1.31
	0.7-1.0	8	1.15	0.060	1.01	0.90	1.05
	1.0-1.5	6	1.48	0.102	1.18	0.73	0.88
	mean of the factors for the groups:				1.09		0.97

γ_{M1}^* partial safety factor

material	curve a	curve b	curve c
S500-S700-S960	1.09	0.99	0.91
S460	1.07	0.97	0.88
S420	1.16	1.05	0.96

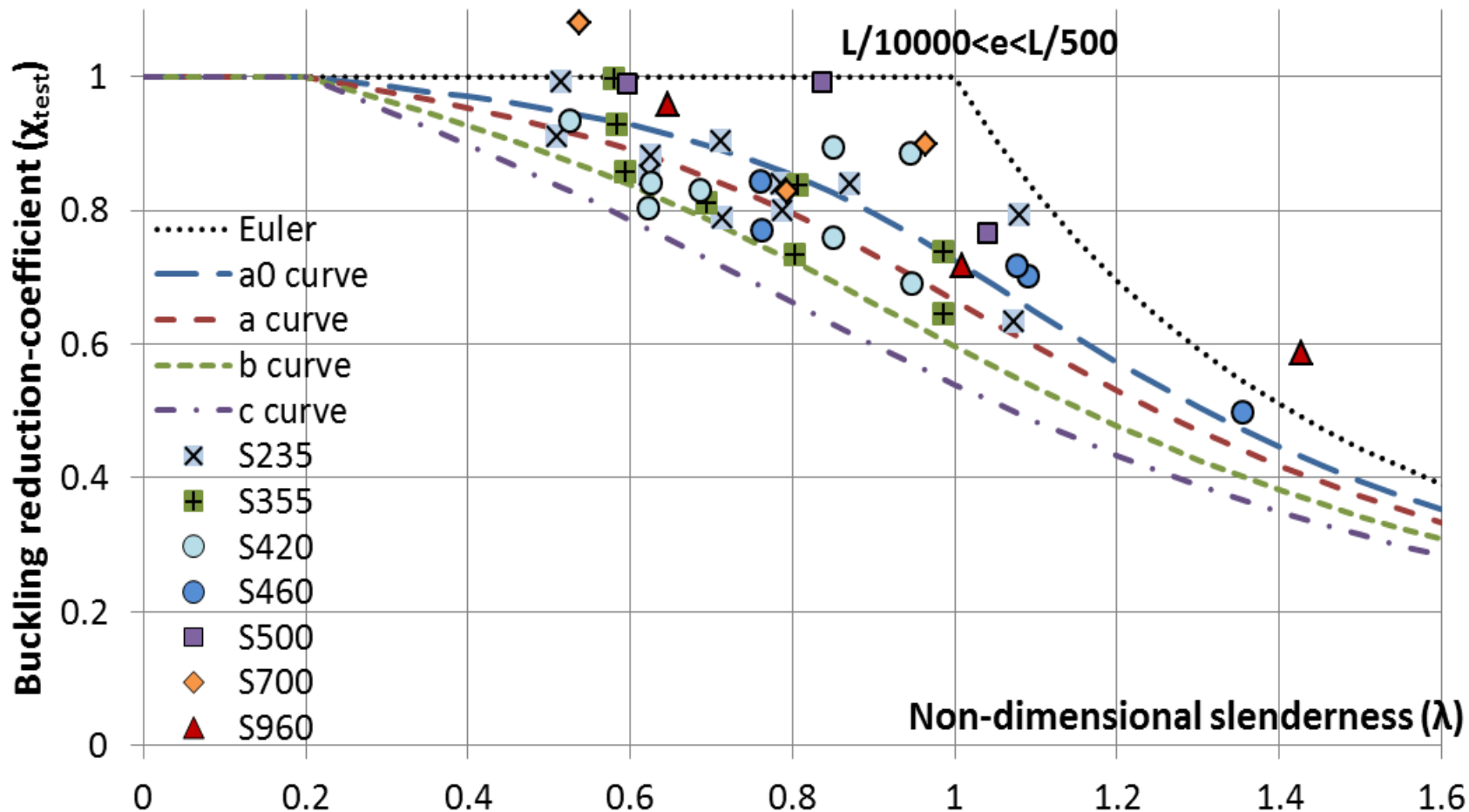
Statistical evaluation shows:

- **buckling curve b** is sufficient for S460-S500-S5700-S960 sections.
- **buckling curve c** is sufficient for S420 sections.



Flexural buckling tests on welded specimens

- The buckling load is always **higher than the buckling curve b**.
- New test results are in good agreement with test results from literature.



Flexural buckling tests on welded specimens

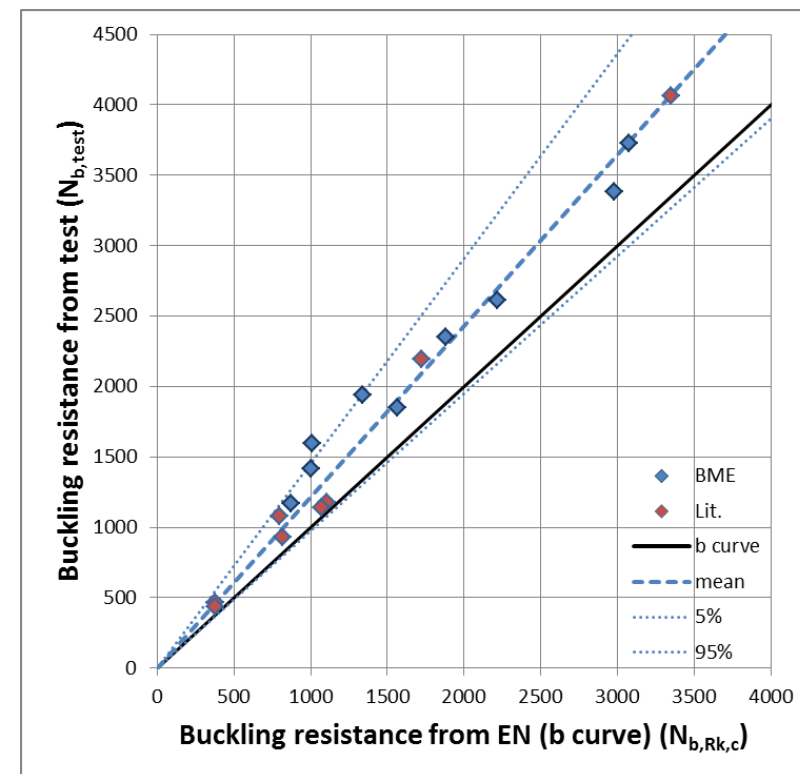
- Statistical evaluation made based on γ_{M1}^* partial safety factor

b curve								
Type	Specimens	λ_{gl}	n	b	V_{δ}	$k_{2.3\%}$	Δk	γ_{M1}^*
Welded	BME	all	9	1.22	0.113	0.95	0.90	1.10
		0.5-0.8	4	1.17	0.038	1.08	0.87	0.99
		0.8-1.5	5	1.29	0.098	1.04	0.84	1.01
		mean of the factors for the groups:					1.06	
	BME Rasmussen Ban	all	17	1.22	0.109	0.95	0.90	1.10
		0.5-0.8	6	1.16	0.065	1.01	0.90	1.04
		0.8-1.1	6	1.27	0.095	1.03	0.85	1.02
		1.1-1.8	5	1.25	0.120	0.95	0.89	1.10
		mean of the factors for the groups:					0.99	

- Statistical evaluation shows that the **buckling curve b** is sufficient for the examined S500-S5700-S960 sections.

γ_{M1}^* partial safety factor

material	curve a	curve b	curve c
S500-S700-S960	1.12	1.00	0.90



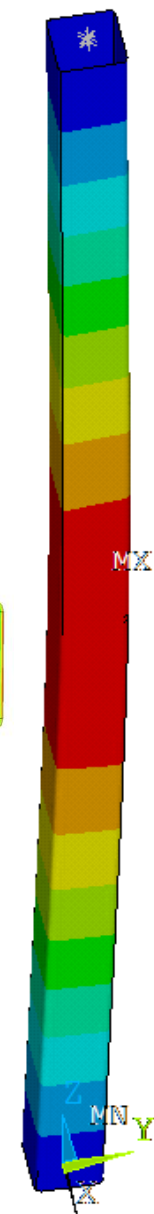
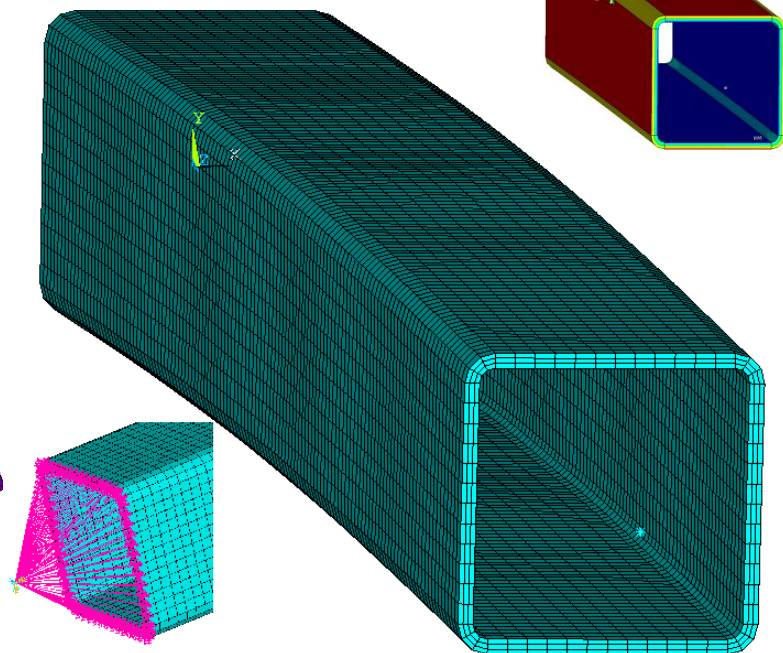
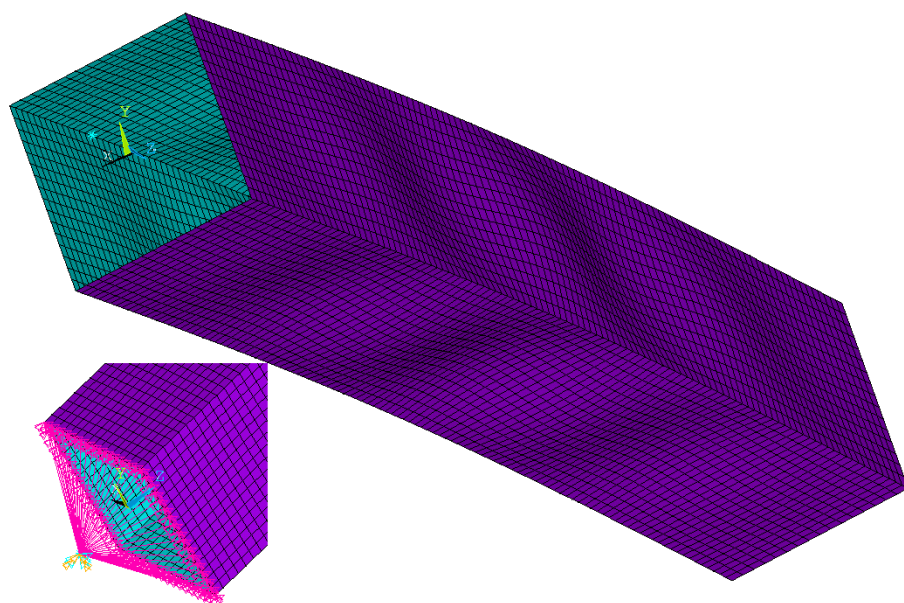


***Numerical flexural buckling analysis
and
buckling curve development***

Numerical analysis

Specifications of the numerical model:

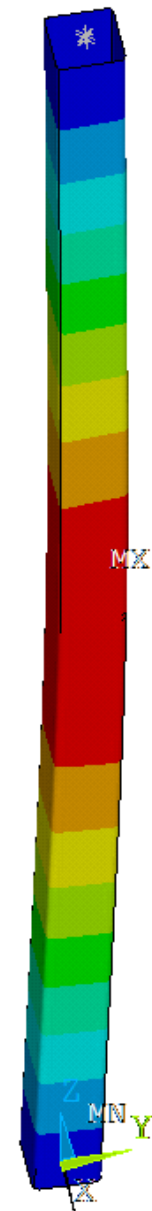
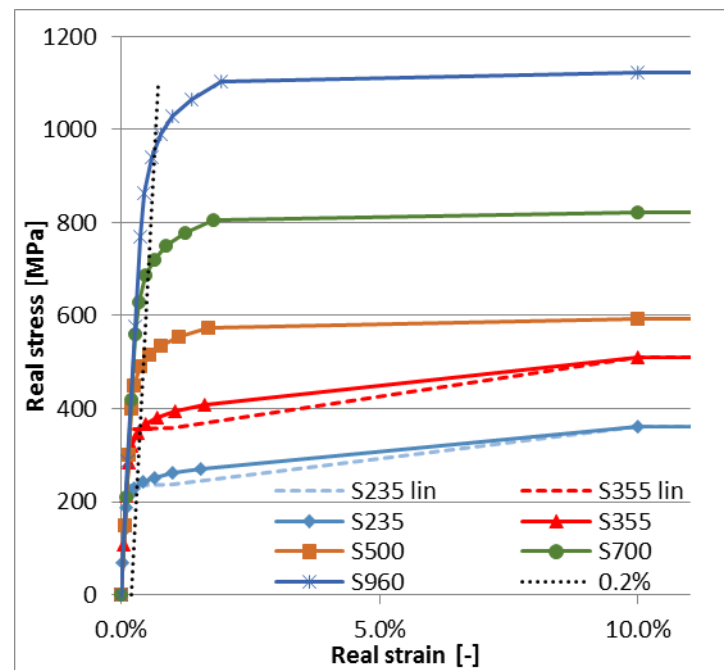
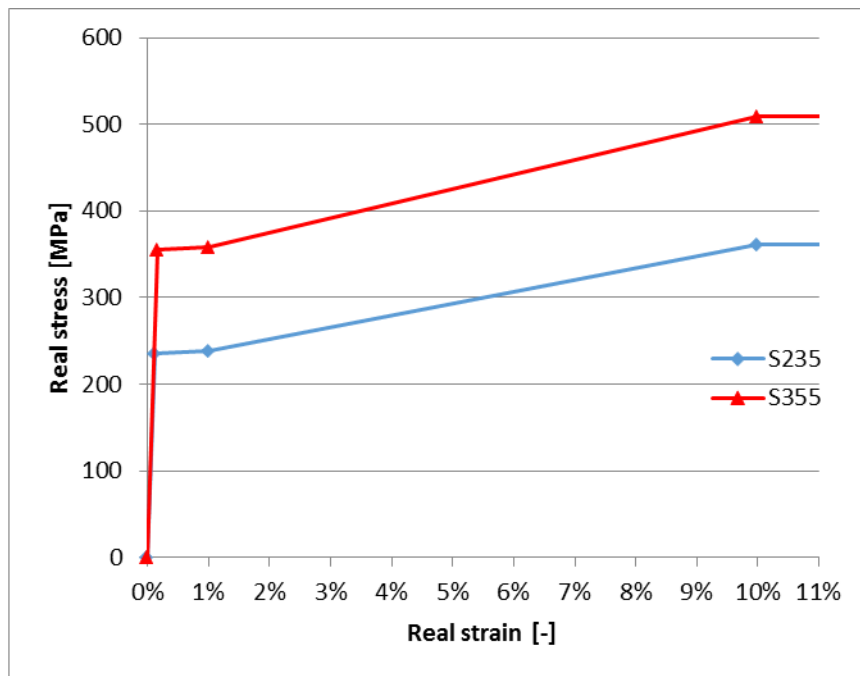
Welded	Cold-formed
Shell model	Solid model
GMNI analysis	
Global imperfection = $L/1000$ (+ local imp.= $0.7 \times b/1000$)	
Residual stress is considered based on new RS model	



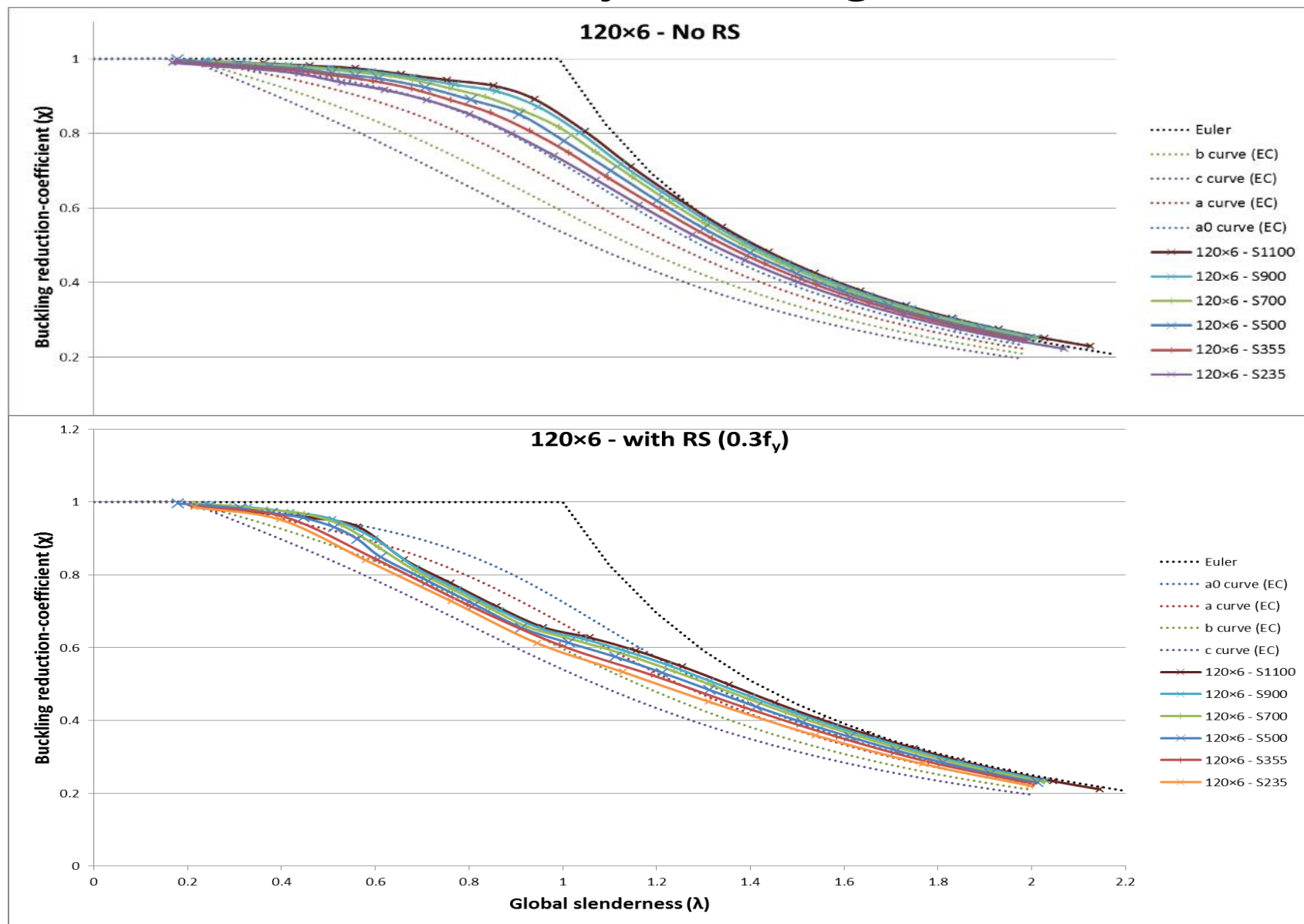
Numerical analysis

Material model used in the analysis:

NSS: S235-S355	HSS: S500-S700-S960
Linear elastic, linear hardening with yield plateau	Ramberg-Osgood type material law

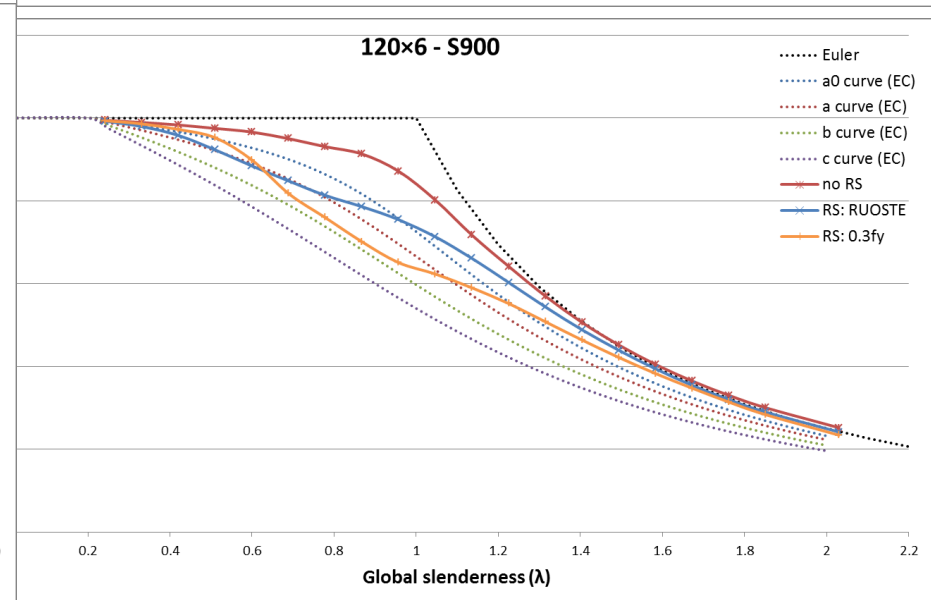
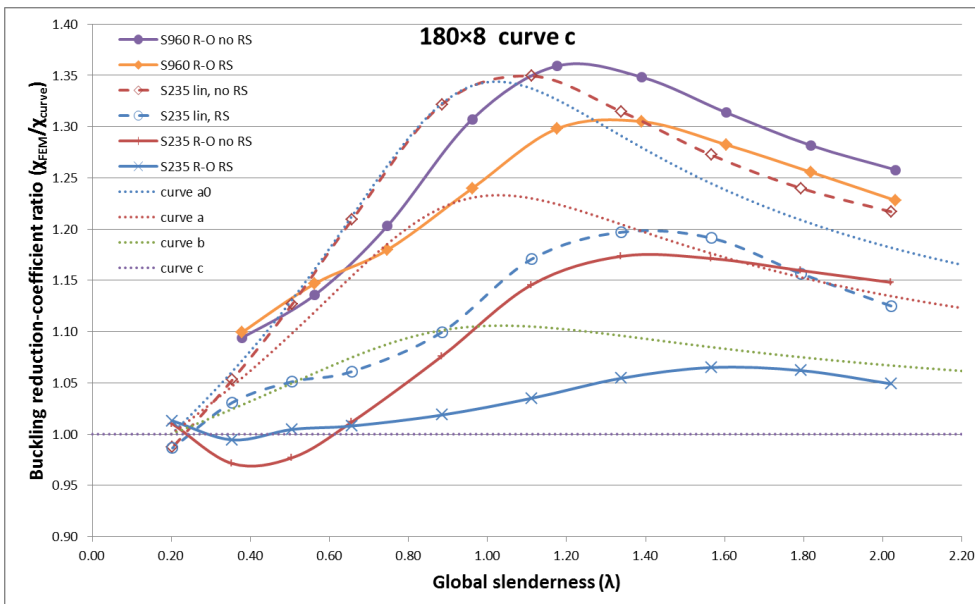
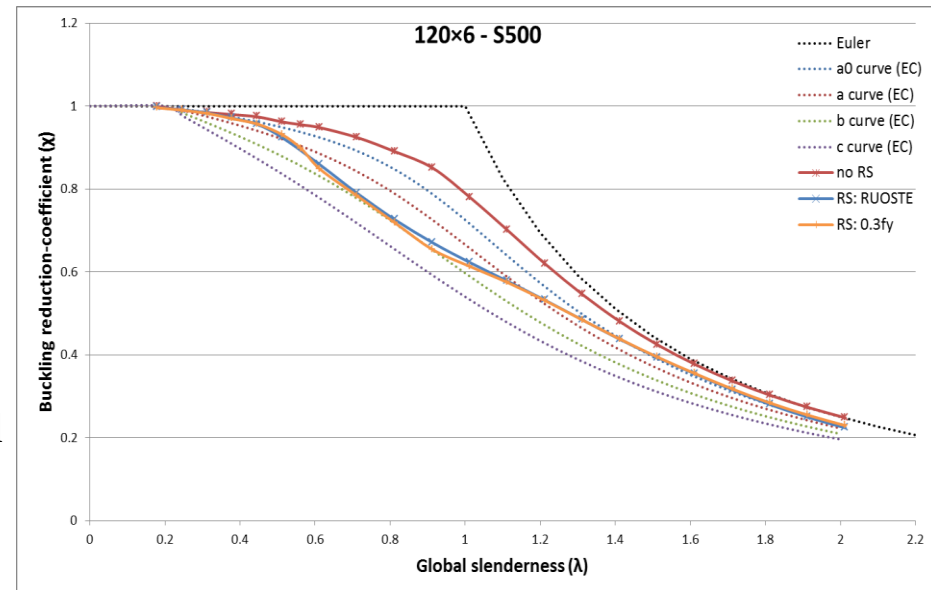


Effect of yield strength

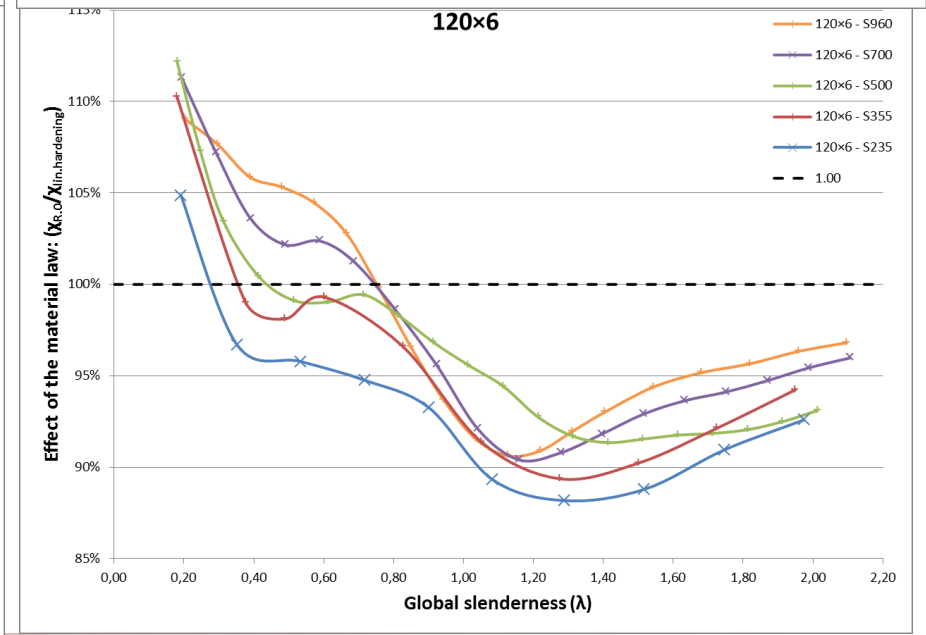
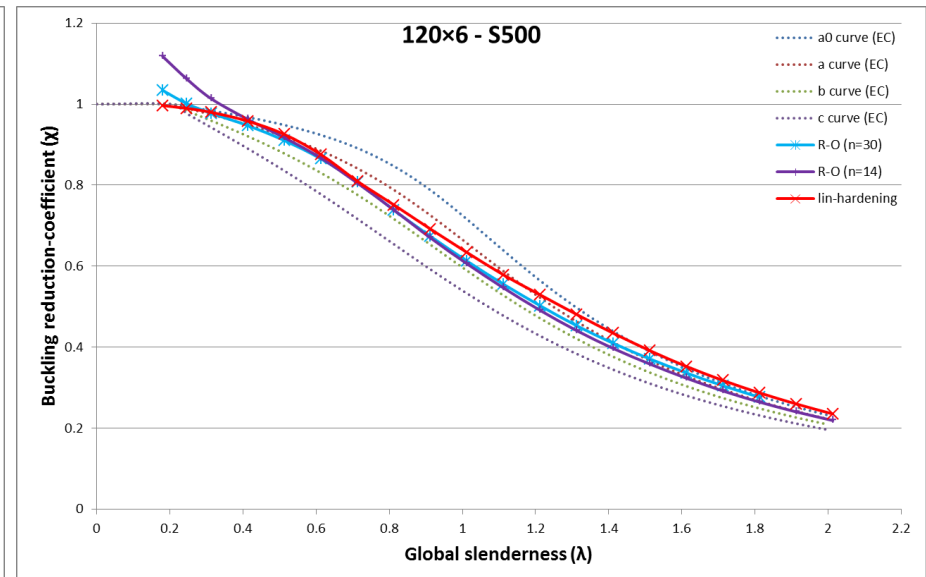
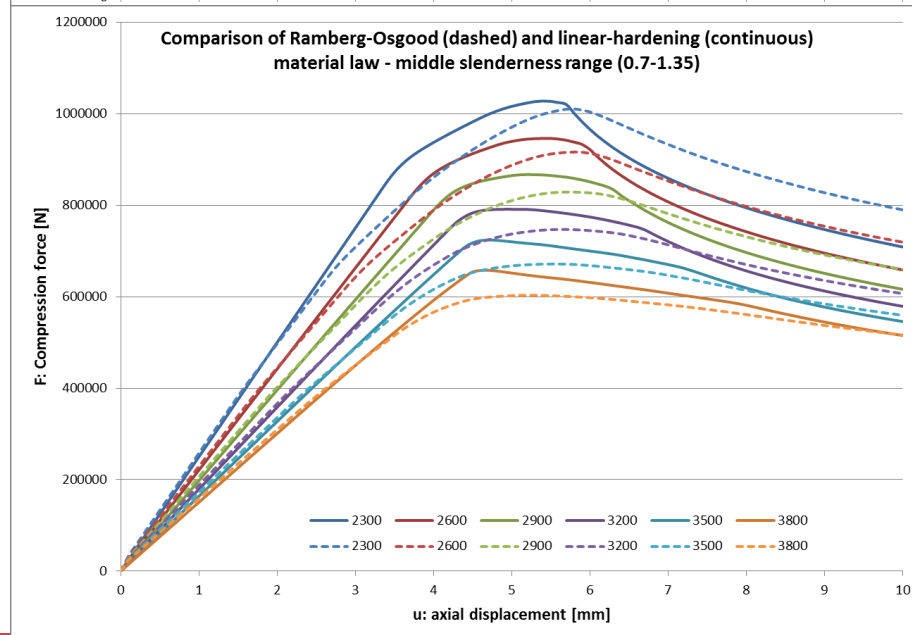
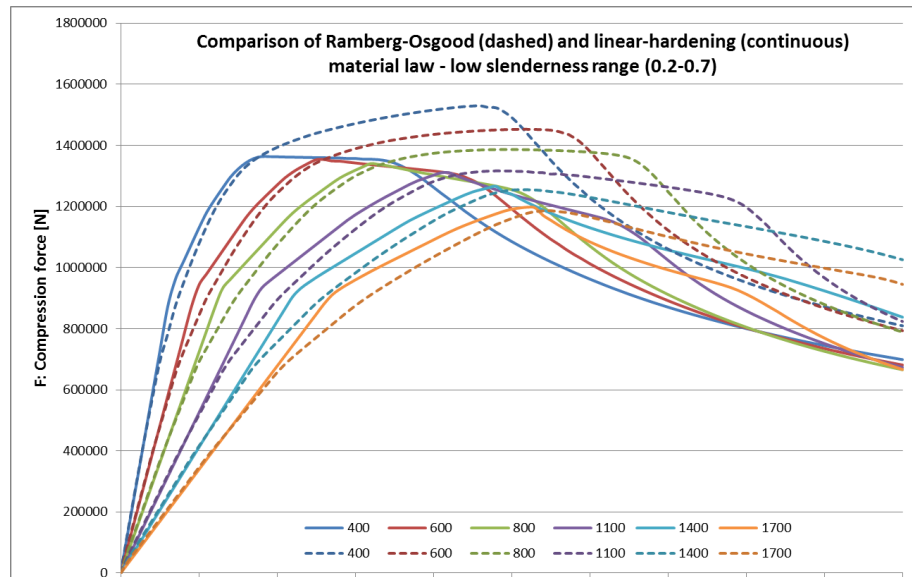


Effect of residual stress

- Residual stress has considerable buckling resistance-reduction effect.
- The effect is reduced with the increasing of the yield strength. (due to the nature of the residual stress).
- The effect is more considerable if linear-hardening material law is used compared to Ramberg-Osgood material law.

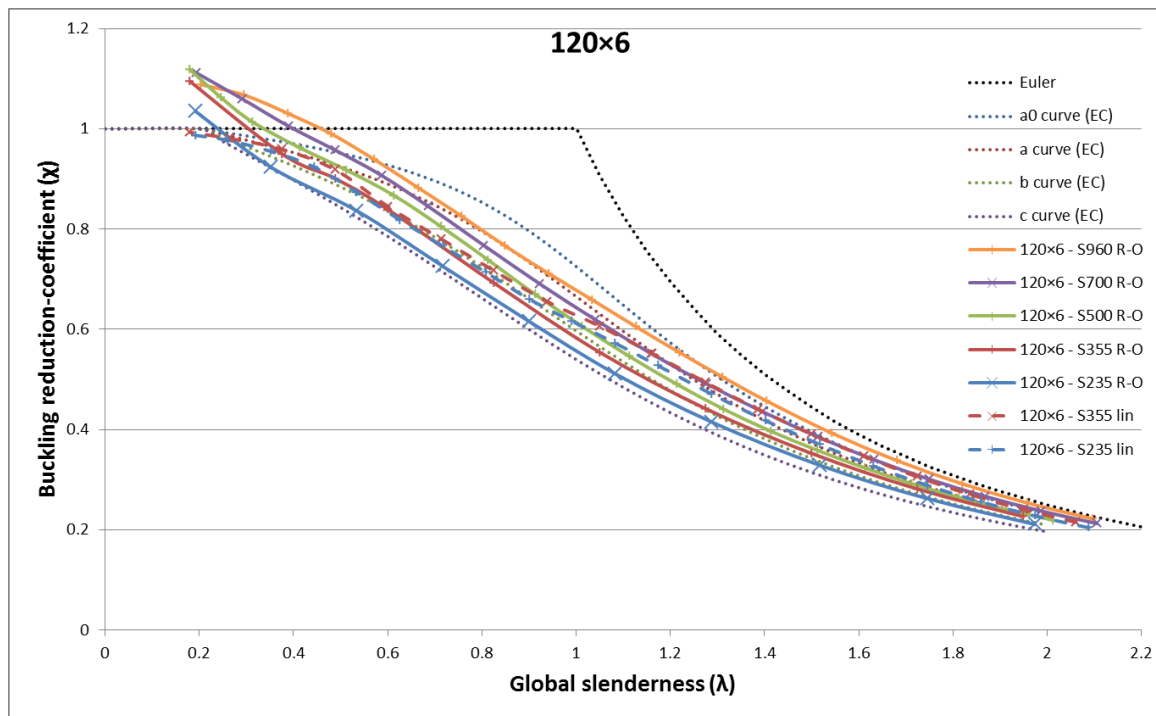


Effect of the material law



Buckling curve development

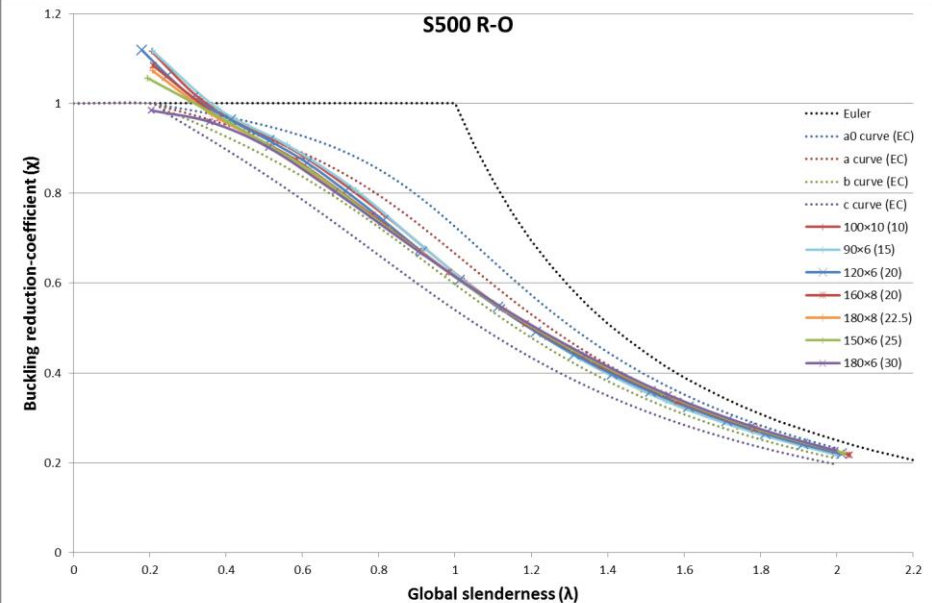
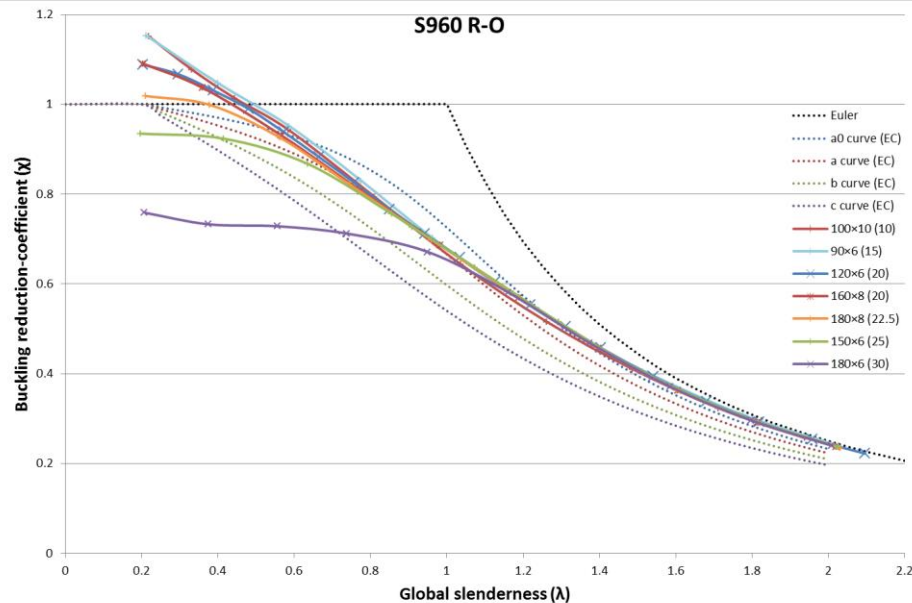
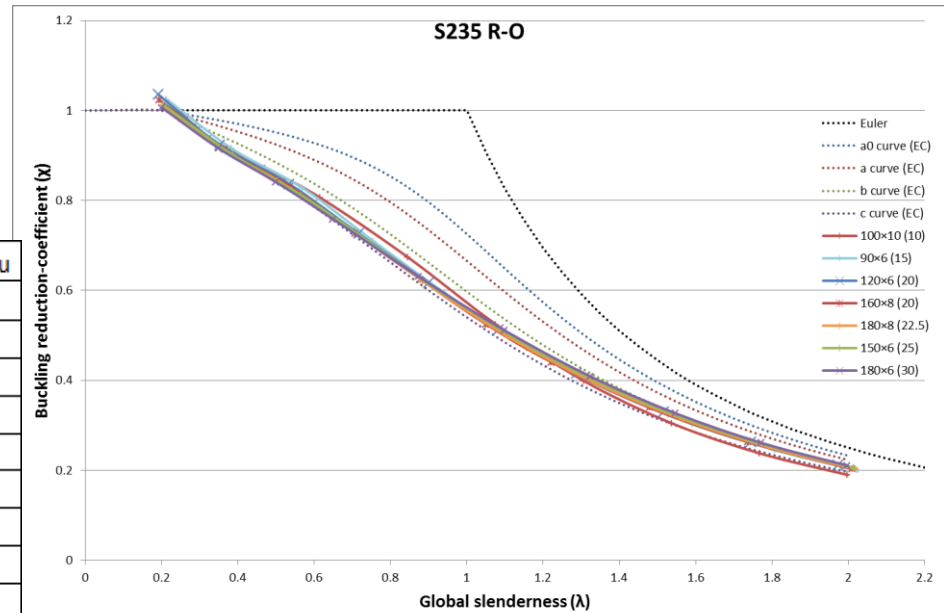
- HSS has increased buckling resistance, because:
 - Higher yield strength, while the out-of-straightness is not higher,
 - Residual stress is not increasing with the increasing of the yield strength,
 - The effect of the residual stress is less considerable in case of Ramberg-Osgood type material law,
 - The nature of the HSS type material law may decrease the resistance in a specific slenderness region ($\sim 0,7 - \sim 1,5$).



Buckling curve development

- Several cross-sections are investigated and the buckling curve b proved to be sufficient for HSS:

Km.	b/t	Ramberg-Osgood					with yield plateau	
		S235	S355	S500	S700	S960	S235	S355
100×10	10	0.90	0.95	1.04	1.09	1.11	0.99	
90×6	15	0.94	0.98	1.04	1.08	1.12	0.99	
120×6	20	0.93	0.98	1.03	1.06	1.09	0.99	1.00
160×8	20	0.93	0.97	1.02	1.05	1.09	0.98	
180×8	22.5	0.92	0.97	1.02	1.05	1.07	0.99	
150×6	25	0.93	0.97	1.02	1.06	1.11	0.99	
180×6	30	0.93	0.97	1.01	1.03	1.15	0.99	
Min		0.90	0.95	1.01	1.03	1.07	0.98	1.00

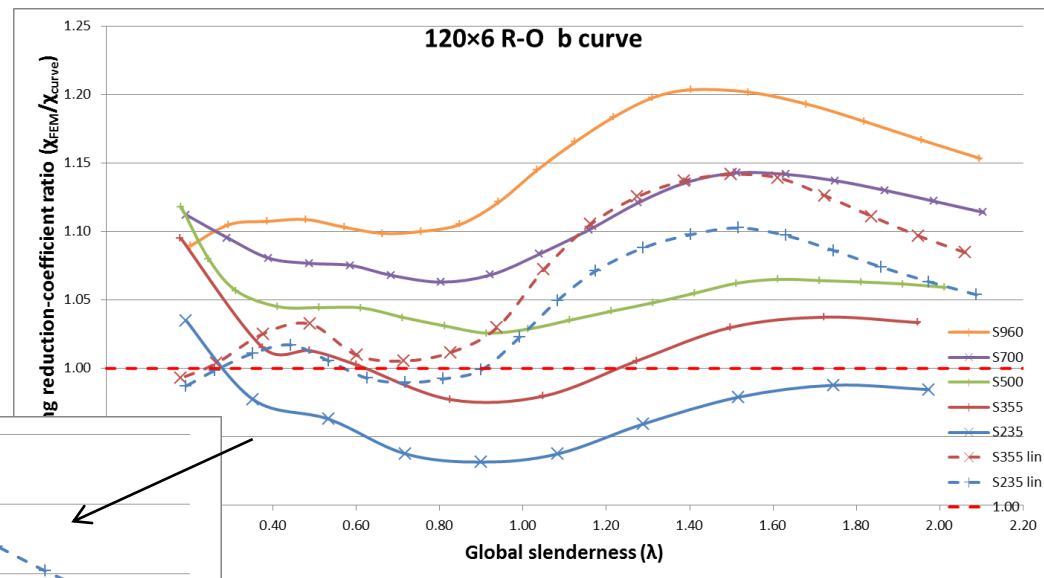


Development of new type of buckling curve

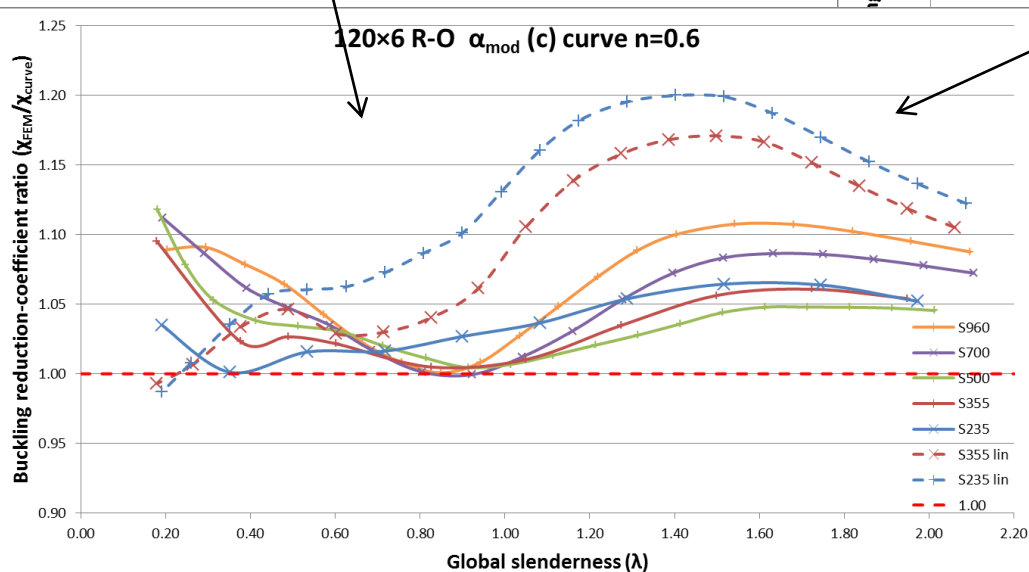
- Resistance model can be found in literature is verified based on numerical results:

$$\alpha = \alpha_0 \cdot \left(\frac{235 \text{ MPa}}{f_y} \right)^n \quad n = 1$$

$$\alpha = 0.49 \cdot \left(\frac{235 \text{ MPa}}{f_y} \right)^{0.6}$$



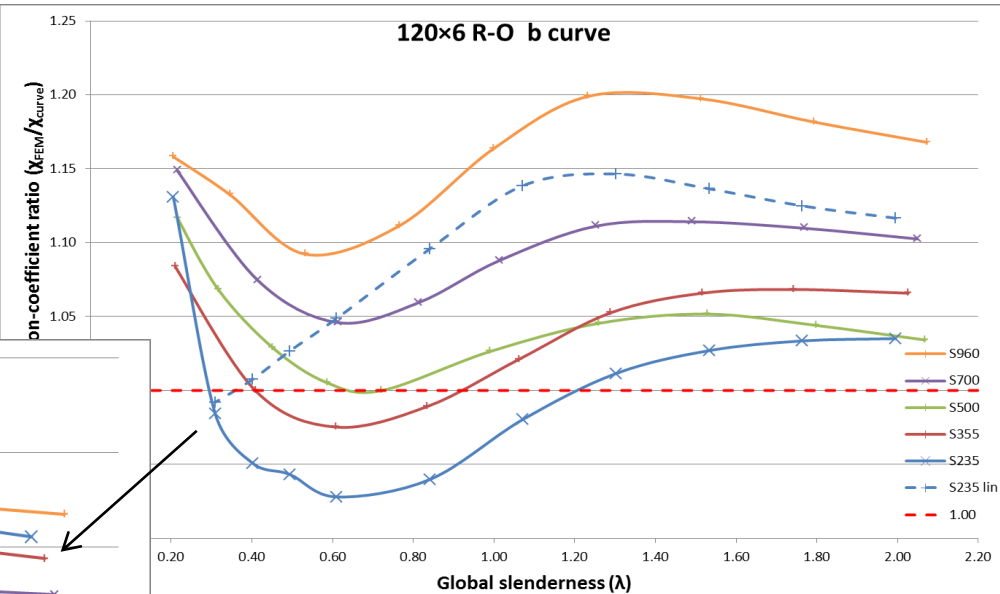
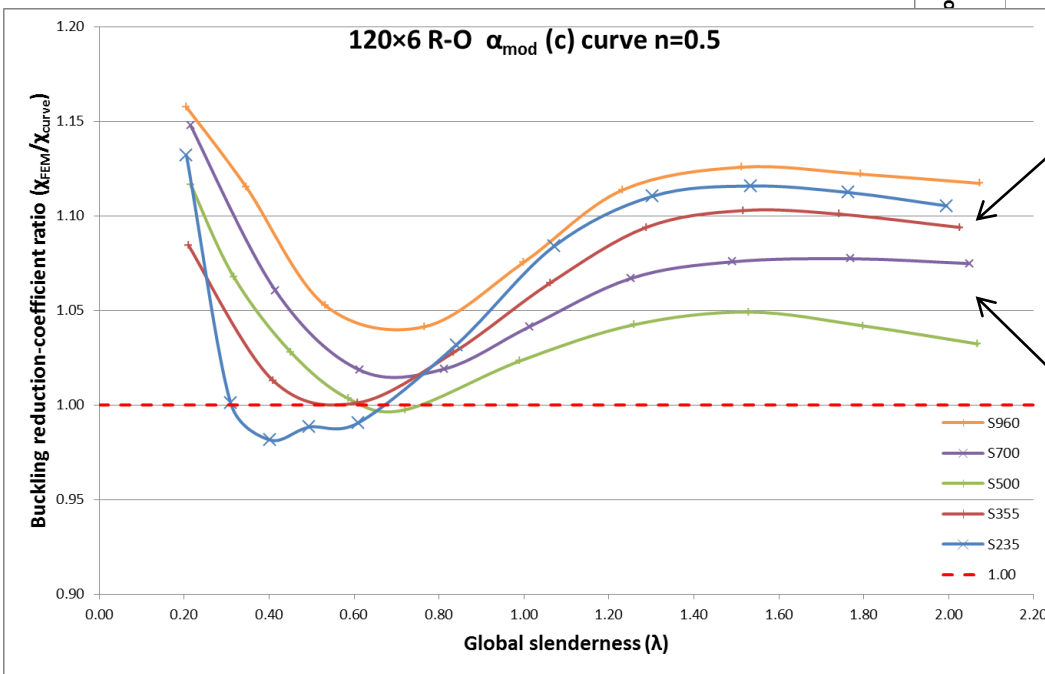
120×6 R-O α_{mod} (c) curve n=0.6



Buckling curve development – cold-formed sections

- For cold-formed sections similar analysis is executed and similarly, the buckling curve b proved to be sufficient for HSS material grades (S500, S700, S960).

Σk_{min} - curve b						
Km.	b/t	Ramberg-Osgood				
		S235	S355	S500	S700	S960
100×10	10	0.97	1.01	1.04	1.09	1.14
120×6	20	0.93	0.98	1.00	1.05	1.09
150×6	25	0.93	0.97	0.99	1.03	1.08
Min		0.93	0.97	0.99	1.03	1.08



- The modified α method can be used with $n=0.5$ for cold-formed specimens:

$$\alpha = 0.49 \cdot \left(\frac{235 \text{ MPa}}{f_y} \right)^{0.5}$$

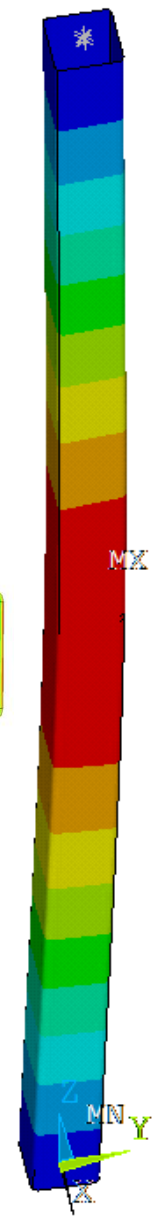
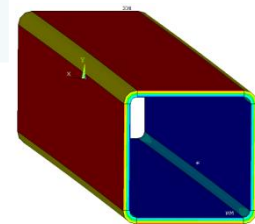
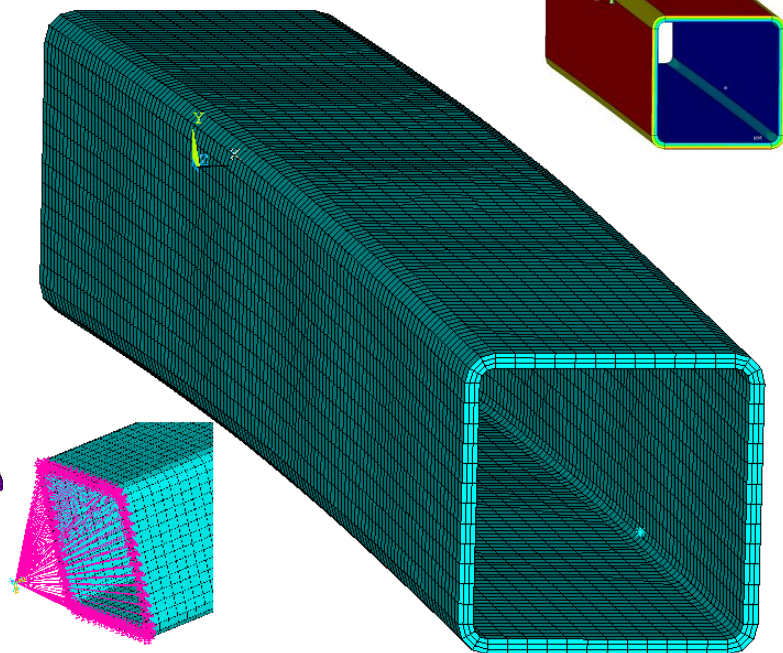
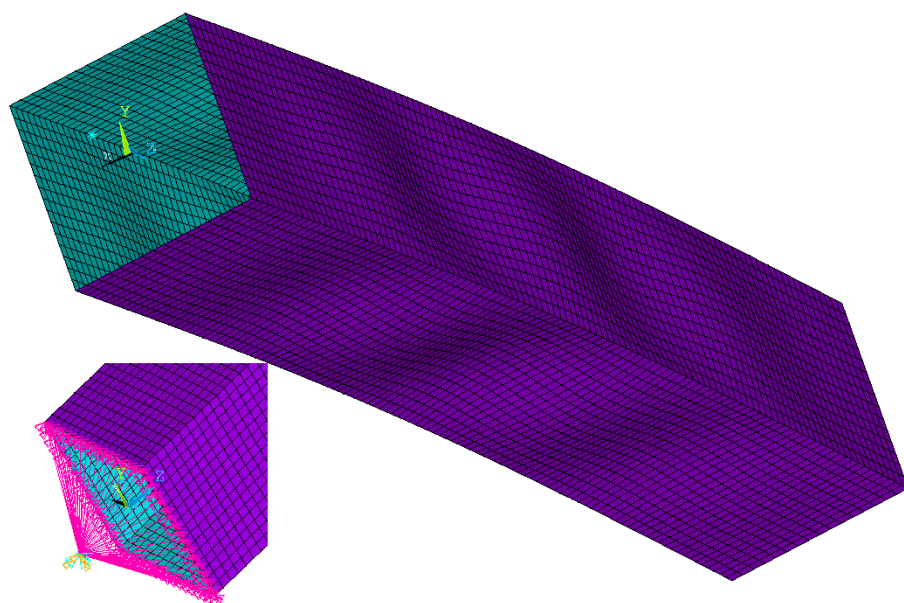


***Stochastic numerical study
for flexural buckling
and
buckling curve development***

Numerical model

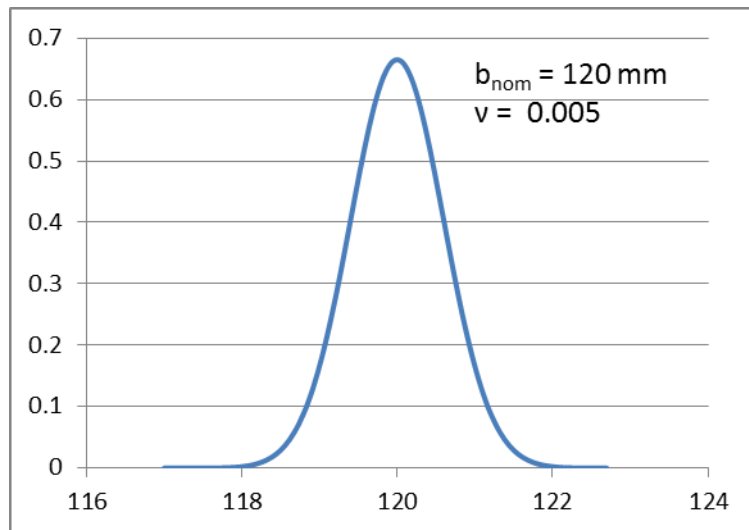
Same numerical model as before, but parameters are treated as variables:

Variable		Distribution type	Mean value	CoV
width	b	Gauss (Normal)	Nominal	0.005
thickness	t	Gauss (Normal)	Nominal	0.05
yield strength #1	f_y	Lognormal	Nominal/0.8892	0.07
yield strength #2	f_y	Lognormal	Nominal/0.9199	0.05
compressive residual stress	σ_c	Gauss (Normal)	Calculated from nominal values	0.17
global imperfection	v_0	Gamma	Based on experimental result	

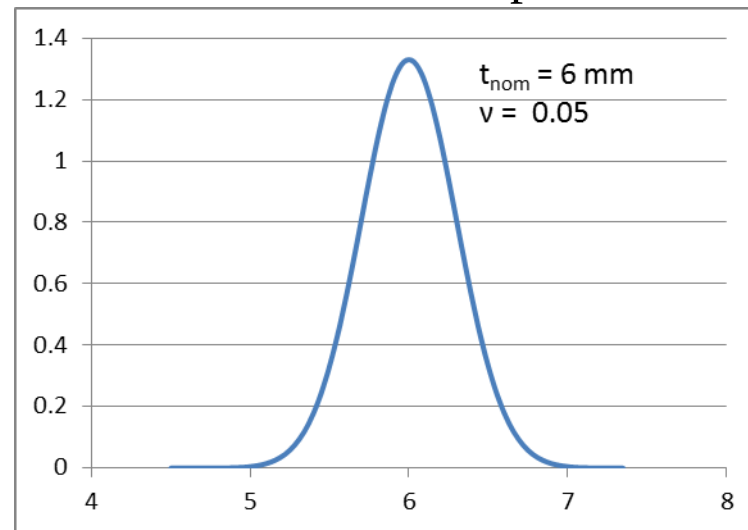


Variables

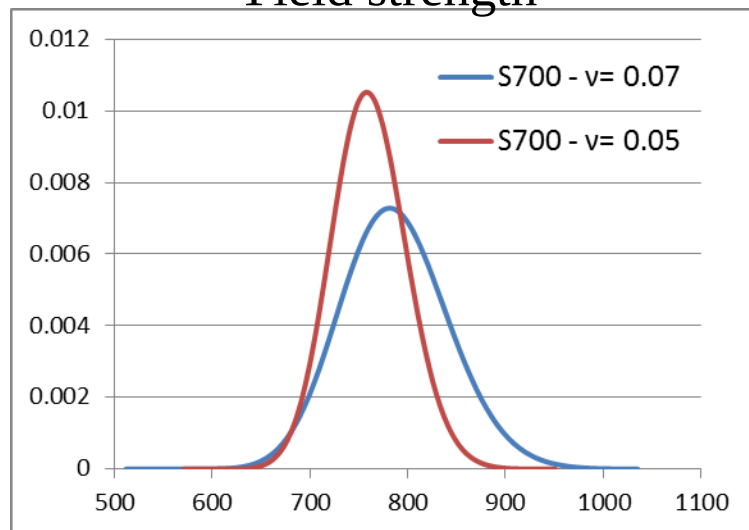
Width of the cross section



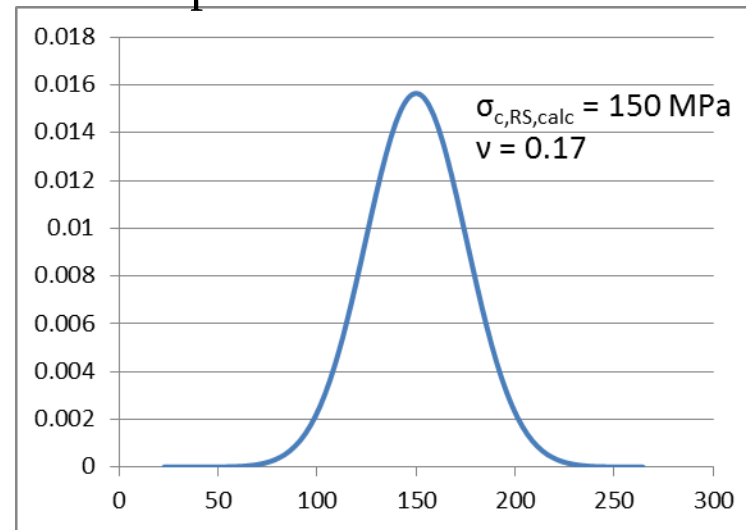
Thickness of the plates



Yield strength

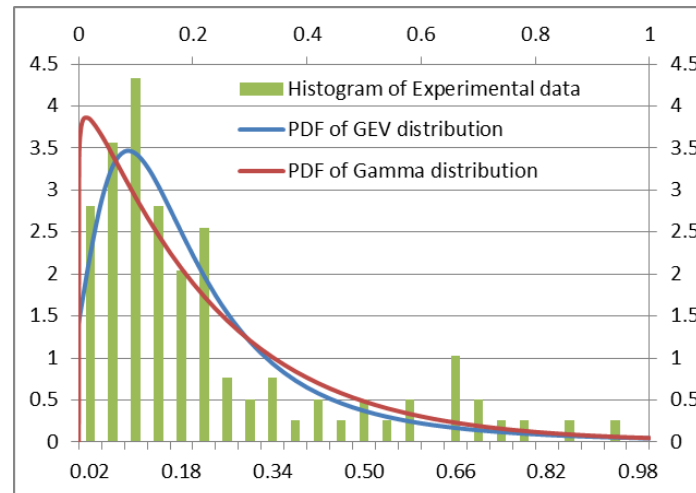
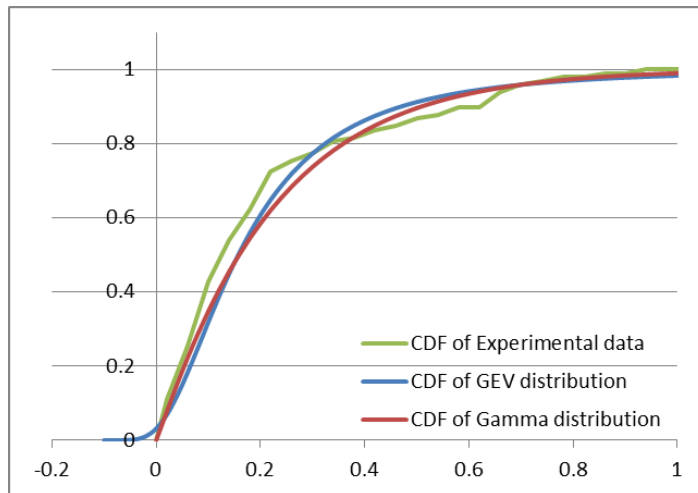


Compression residual stress



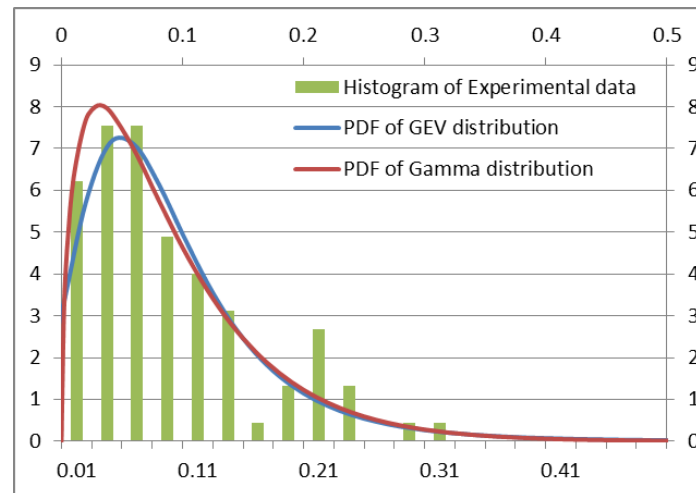
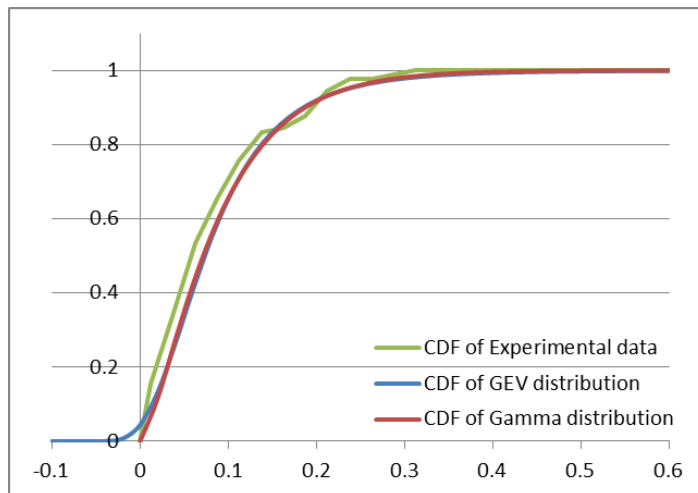
Variables

Geometrical imperfection for welded columns:



Gamma distribution:
 $\alpha = 1.063$
 $\beta = 0.211$

Geometrical imperfection for cold-formed columns:

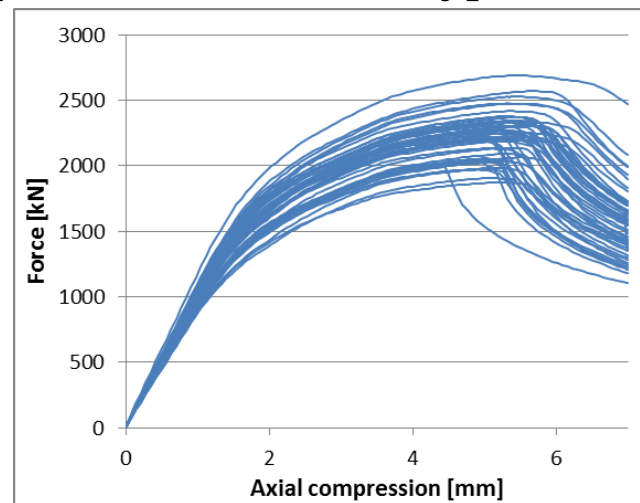
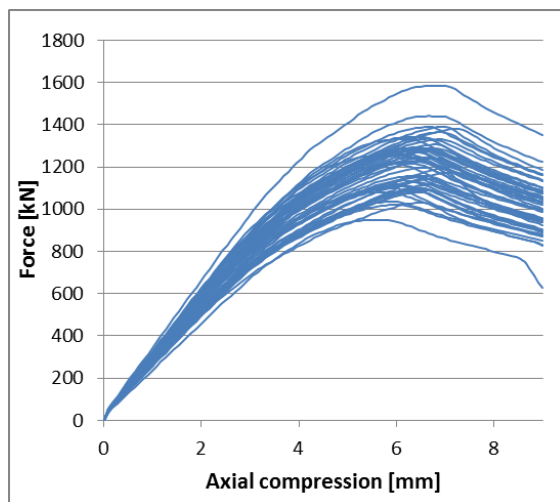


Gamma distribution:
 $\alpha = 1.528$
 $\beta = 0.059$

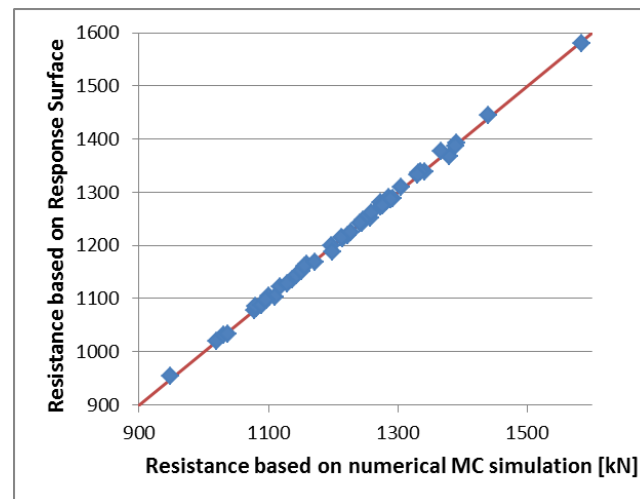
Stochastic analysis

Research strategy:

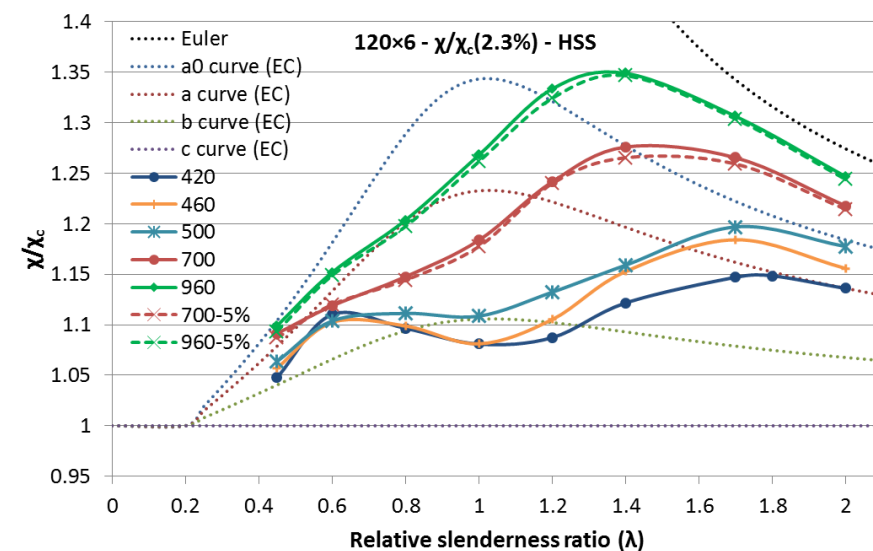
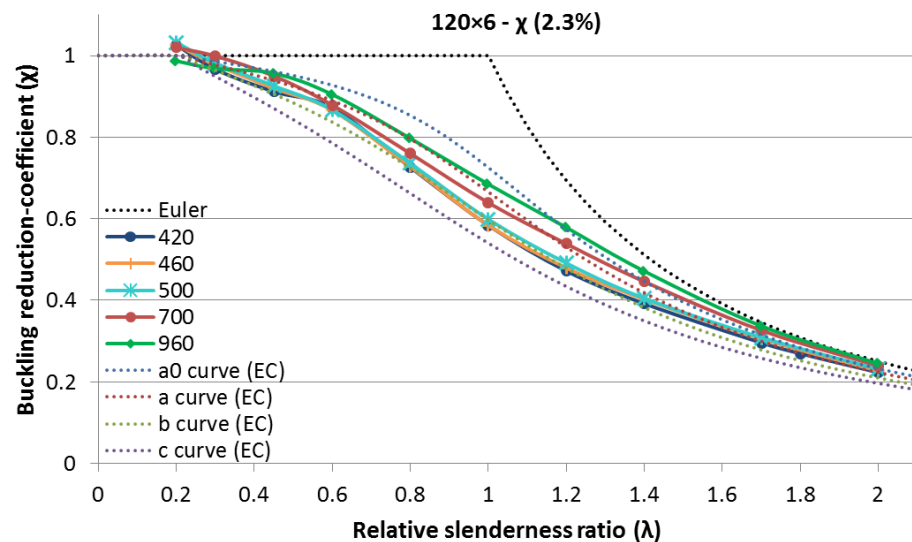
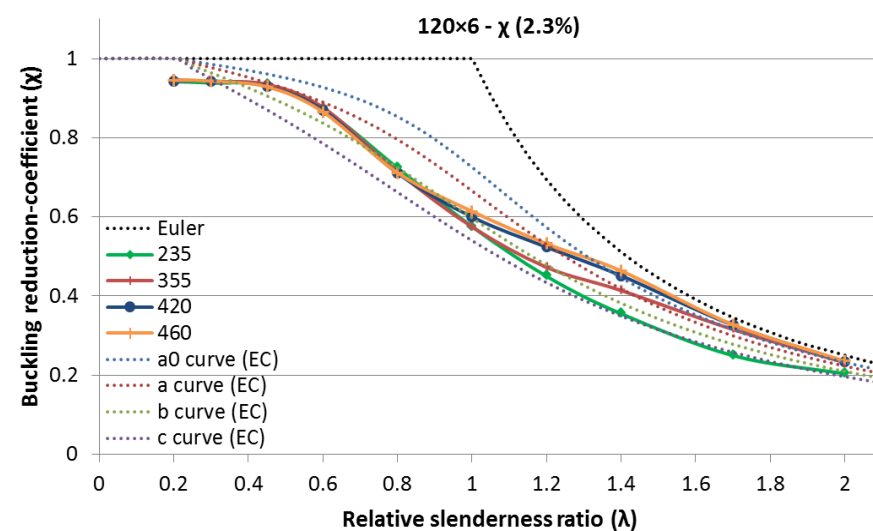
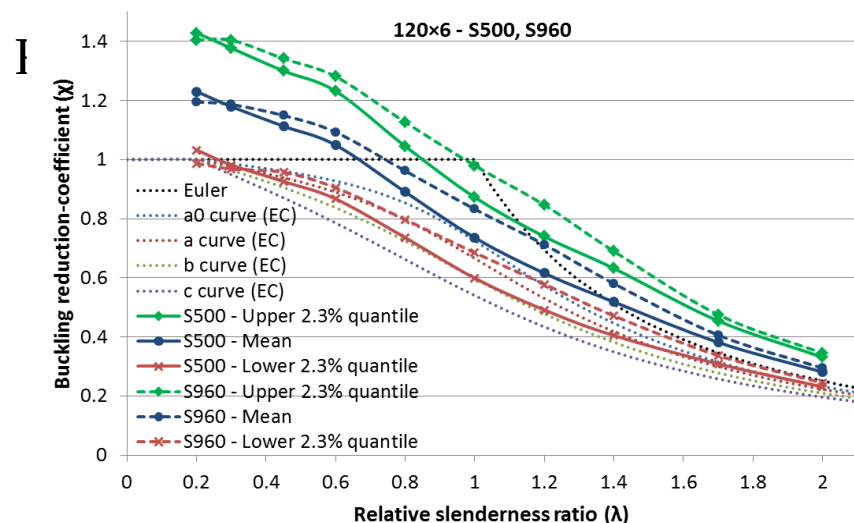
1. Monte Carlo simulation with $n_1=50$ samples and with Latin hypercube sample generation, using the numerical model.



2. Fitting response surface
3. Monte Carlo simulation with $n_2=10000$ samples and with Latin hypercube sample generation, using response surface.
4. Calculation of the lower 2.3% quantile



Stochastic analysis - Results



Buckling curve development

Statistical evaluation based on EN 1990 Annex D and following the concept of Johansson-Maquoi-Sedlacek:

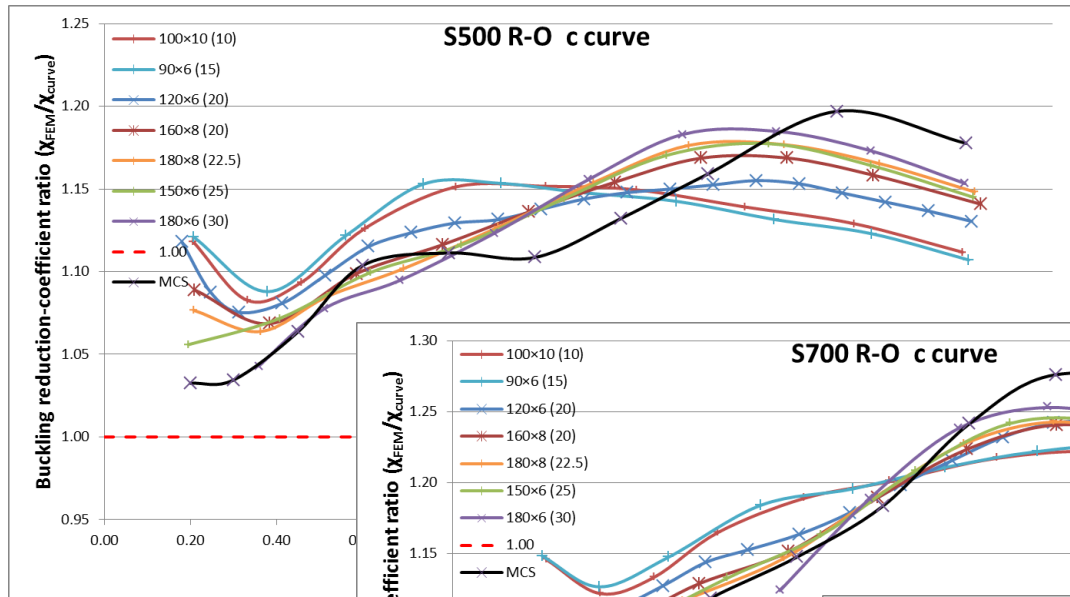
Comparison to:	curve c		curve b		curve a	
Safety approach:	1.	2.	1.	2.	1.	2.
Steel grade	$k_{2.3\%}$	γ_M^*	$k_{2.3\%}$	γ_M^*	$k_{2.3\%}$	γ_M^*
S420	1.05	0.88	0.98	0.95	0.88	1.04
S460	1.06	0.88	0.98	0.95	0.88	1.04
S500	1.06	0.88	1.00	0.94	0.90	1.03
S700	1.09	0.87	1.05	0.92	0.96	0.98
S700-5%	1.09	0.90	1.05	0.95	0.95	1.02
S960	1.10	0.86	1.06	0.89	1.00	0.95
S960-5%	1.09	0.90	1.05	0.93	1.00	0.99

New proposals:

steel grades	buckling curve
S420 - S460	curve c
S500 – S700	curve b
S960	curve a

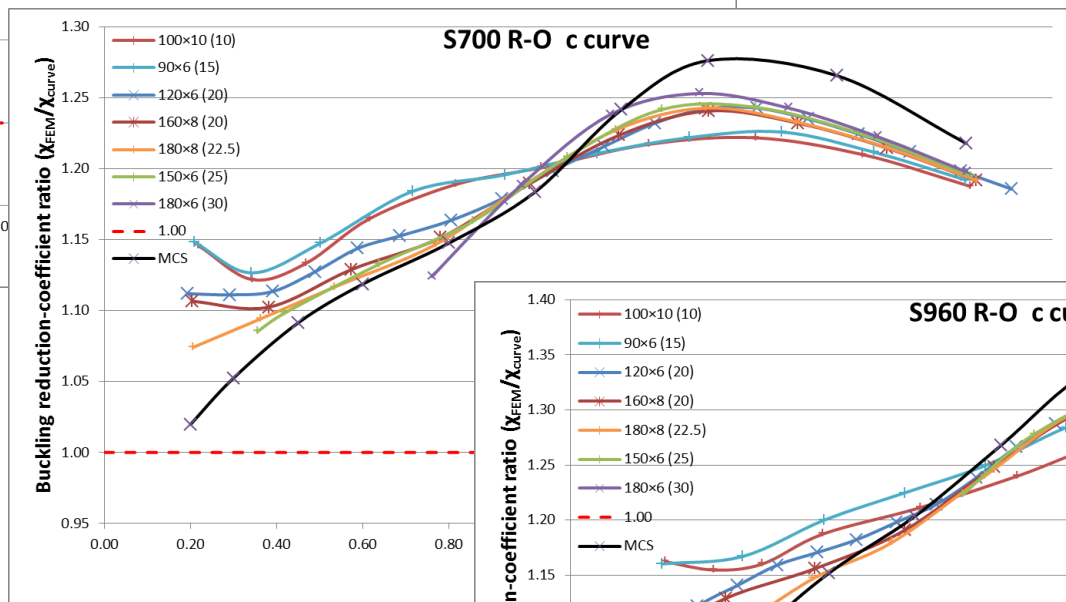


Comparison of deterministic and stochastic results



Results based on
deterministic
analysis:

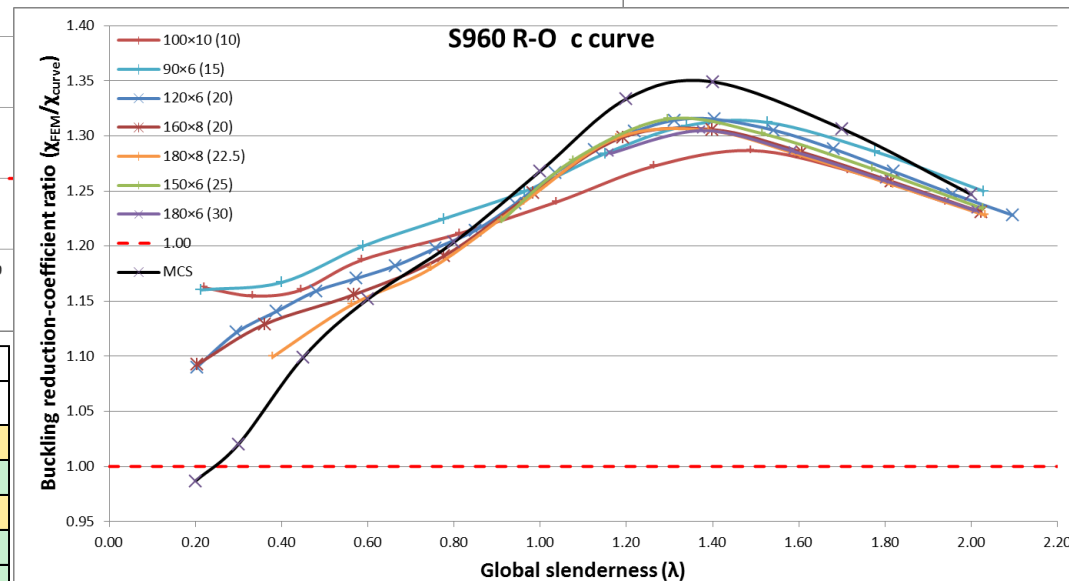
Comparison to curve b		
Material grade	$k_{2.3\%}$	γ_M^*
S500	1.01	0.91
S700	1.03	0.87
S700-5%	1.03	0.90
S960	1.08	0.84
S960-5%	1.08	0.87



Comparison to curve a		
Material grade	$k_{2.3\%}$	γ_M^*
S500	0.92	0.99
S700	0.95	0.96
S700-5%	0.95	0.99
S960	1.00	0.92
S960-5%	1.00	0.95

Results based
on stochastic
analysis:

Comparison to curve b			Comparison to curve a		
Material grade	$k_{2.3\%}$	γ_M^*	Material grade	$k_{2.3\%}$	γ_M^*
S500	1.00	0.94	S500	0.90	1.03
S700	1.05	0.92	S700	0.96	0.98
S700-5%	1.05	0.95	S700-5%	0.95	1.02
S960	1.06	0.89	S960	1.00	0.95
S960-5%	1.05	0.93	S960-5%	1.00	0.99





Thank you for your attention!