ENHANCED DESIGN APPROACH FOR GLOBAL AND LOCAL BUCKLING RESISTANCE OF WELDED BOX-SECTION COLUMNS

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CONTENT

Problem Statement

The problem under study is divided into three parts:

1- Global buckling :

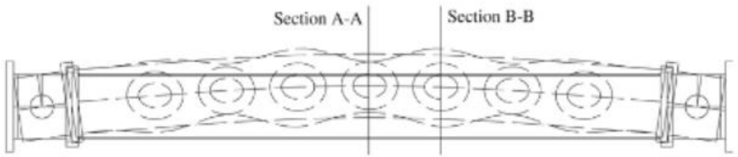
According to the previous studies, the available buckling curves in the Eurocode3 are underestimating the global buckling strength of the high strength steel (HSS) columns.

2- Local buckling:

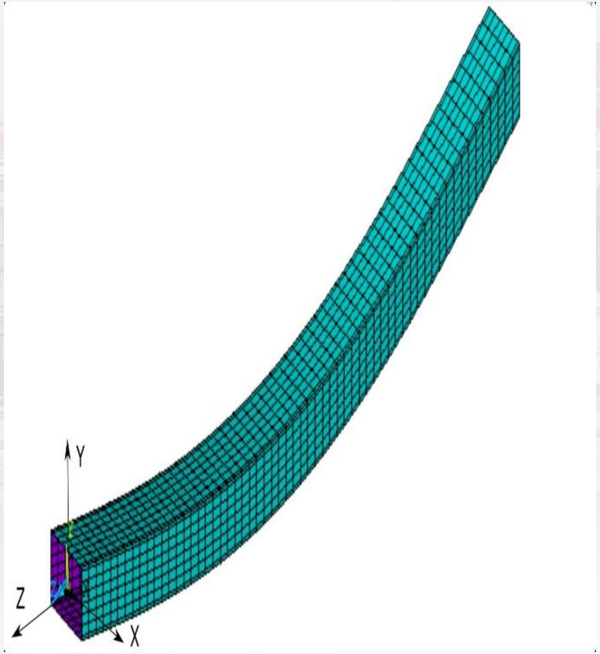
According to the previous studies, the currently used Winter curve in EN 1993-1-5 is overestimating the local buckling strength of the high strength steel columns. In which the difference can reach 15%.

3- Interaction behaviour:

How to combine effective cross-section approach and flexural buckling design?

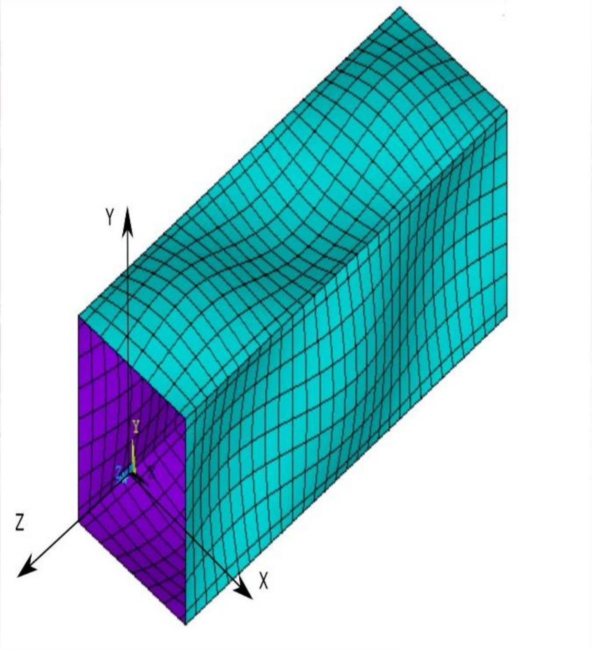


Problem Statement



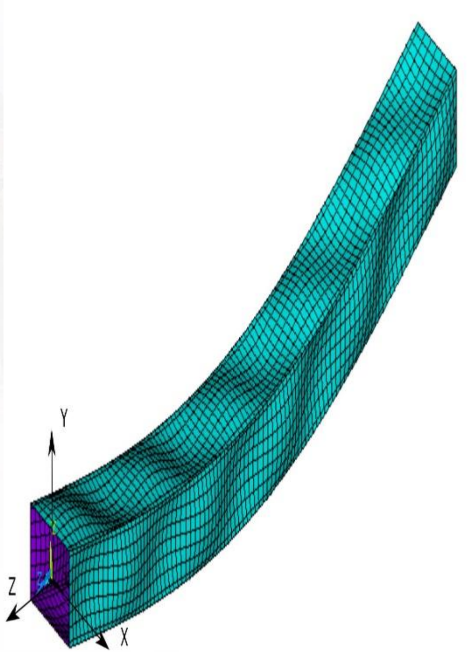
Global buckling

Underestimated for HSS



Local buckling

Overestimated



Interaction buckling

Very limited research

OBJECTIVES

Creation of reliable and accurate design method for interaction buckling problems

Test based design approach

Based on large number of test results (or numerical simulations replacing real tests) and statistical evaluation appropriate buckling curves can be determined.

Numerical model based design

Using appropriate imperfections and non-linear material models the ultimate load can be determined

OBJECTIVES

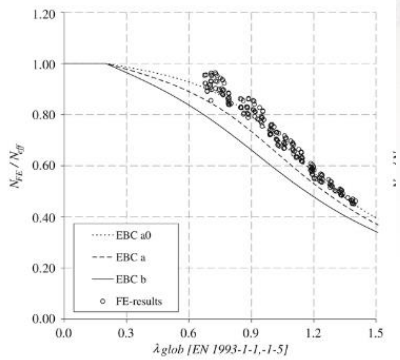
Creation of reliable and accurate design method for interactive buckling problems

Test based design approach

Based on large number of test results (or numerical simulations replacing real tests) and statistical evaluation appropriate buckling curves can be determined.

Large test database needed

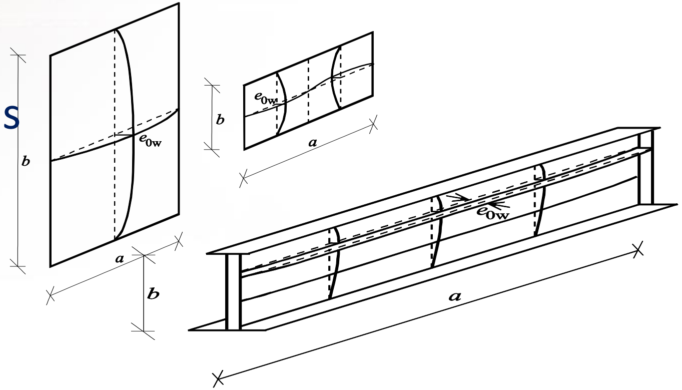
Supplementing test results by accurate numerical model



Numerical model based design

Using appropriate imperfections and non-linear material models the ultimate load can be determined

Accurate imperfections needed



RESEARCH PROGRAM

1. Numerical model development based on previous test results

2. Numerical parametric study on global and local buckling to find the appropriate imperfections and combination of imperfections with residual stresses to determine the accurate ultimate strength of HSS box-section columns.

3. Using the validated and verified numerical model second numerical parametric study to apply the previously obtained imperfections and residual stresses to estimate the strength of columns that have interactive buckling.

4. Statistical evaluation of the numerical results and appropriate design method development.

RESEARCH PROGRAM

Previous stage of research

1. Numerical model development based on previous test results

2. Numerical parametric study on global and local buckling to find the appropriate imperfections and combination of imperfections with residual stresses to determine the accurate ultimate strength of HSS box-section columns.

Current stage of research

3. Using the validated and verified numerical model second numerical parametric study to apply the previously obtained imperfections and residual stresses to estimate the strength of columns that have interaction buckling.

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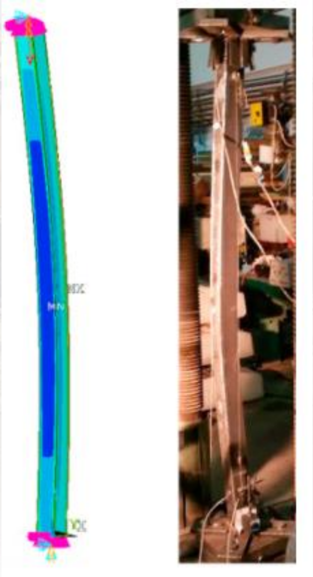
FEM BASED DESIGN - PROBLEM STATEMENT

Global imperfection



L/1000 + residual stresses

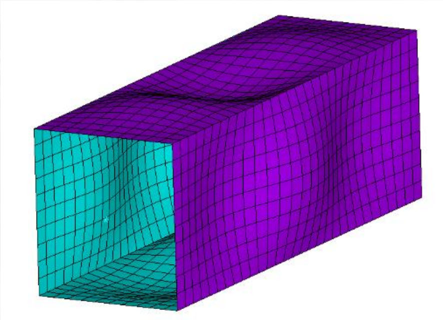
or

equivalent geometric bow imperfection

AC2 Buckling curve according to Table 6.2 AC2	elastic analysis e_0 / L	plastic analysis e_0 / L
a_0	1 / 350	1 / 300
a	1 / 300	1 / 250
b	1 / 250	1 / 200
c	1 / 200	1 / 150
d	1 / 150	1 / 100

Problem: Developed for GNIA and not GMNIA.

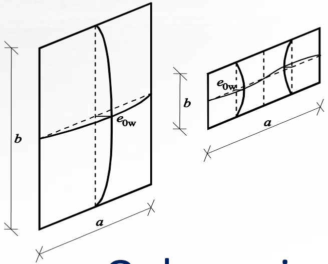
Local imperfection



No previous proposal

and

equivalent geometric imperfection b/200 (referring to Winter-curve)



Only equivalent imperfection is developed and verified to GMNIA.

FEM BASED DESIGN - PROBLEM STATEMENT

in the case of interaction buckling

previous studies showed if equivalent imperfections for global and local buckling are added

L/200 + min(a/200;b/200)

results will be far on the safe side

Reason: duplication of residual stresses (theoretically not correct)

for global: L/1000 + Residual stresses

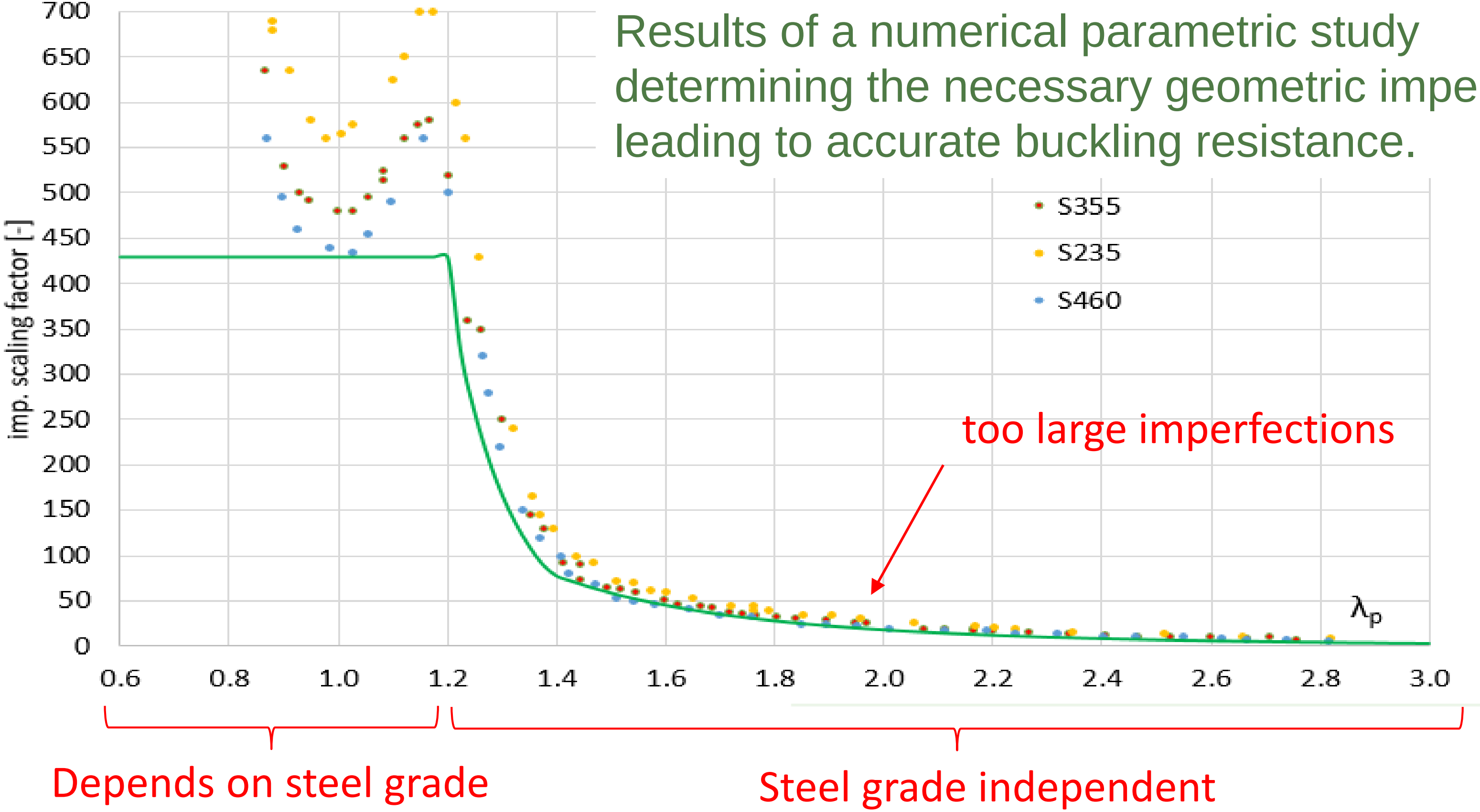
for local: ???? No validated value

Improvement needed

Validation of geometric imperfection with residual stresses.

LOCAL BUCKLING- GEOMETRIC IMPERFECTION

Results of a numerical parametric study determining the necessary geometric imperfections leading to accurate buckling resistance.



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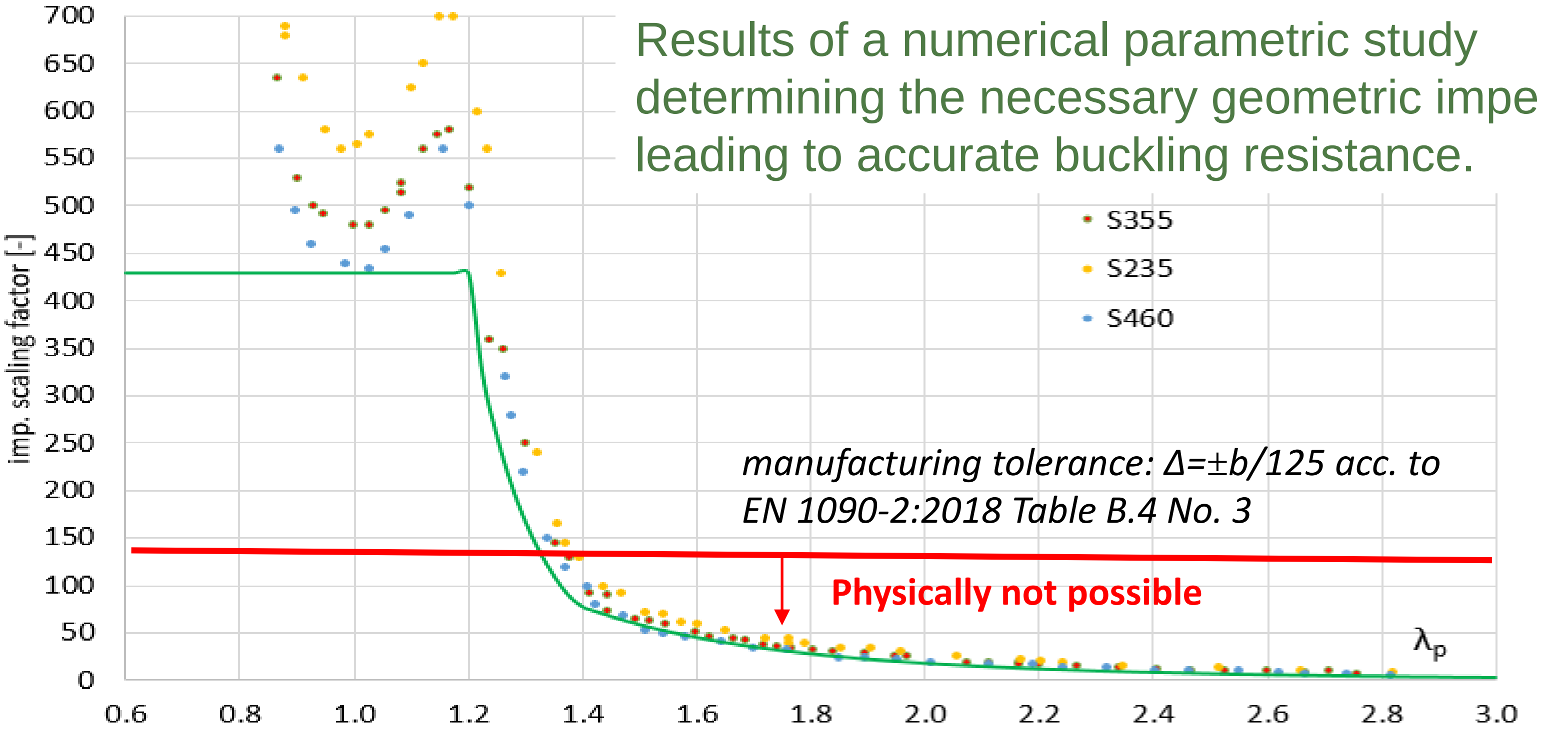
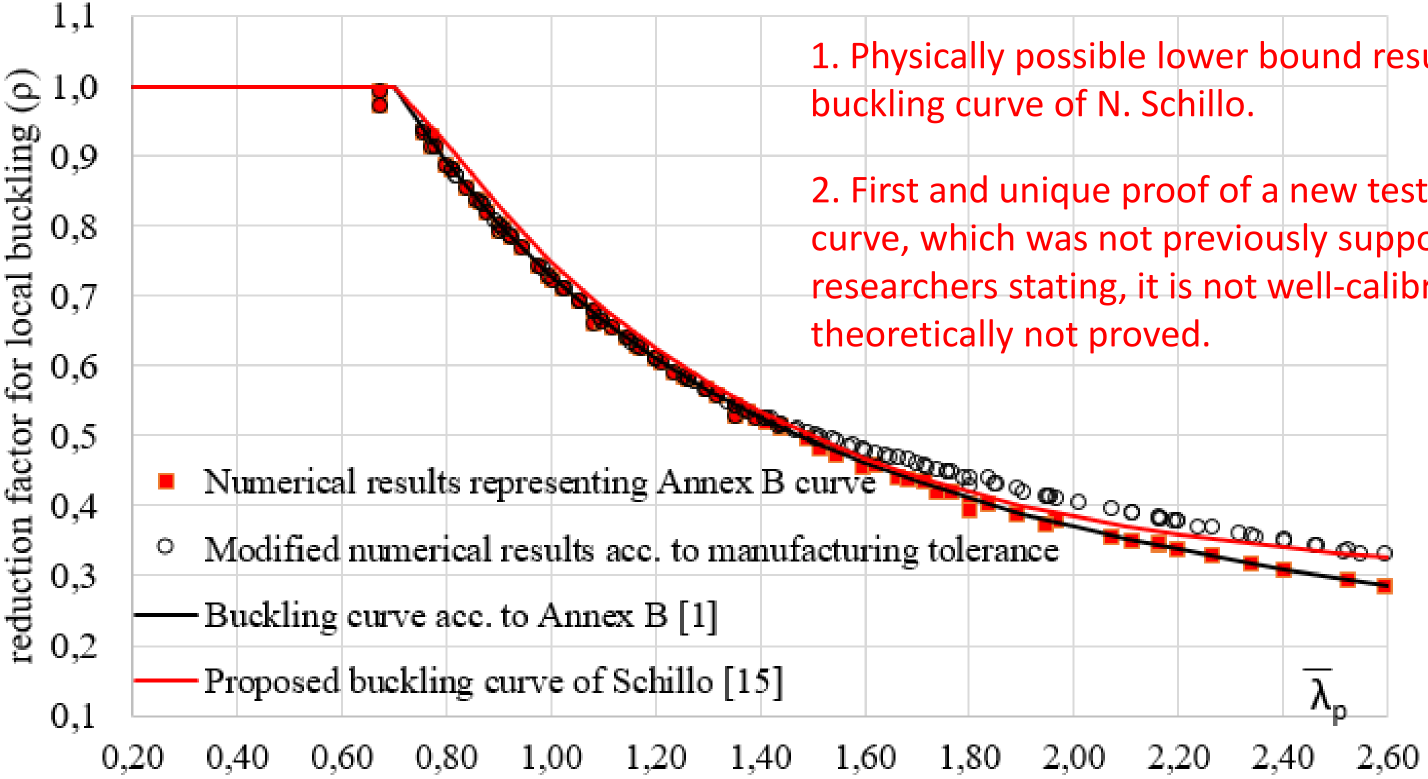


Annex B curve is safe sided and does not give the accurate solution for slenderness ratio larger than 1.3.

MODIFIED BUCKLING RESISTANCE CONSIDERING MANUFACTURING TOLERANCE



1. Physically possible lower bound results fit to buckling curve of N. Schillo.

2. First and unique proof of a new test based buckling curve, which was not previously supported by researchers stating, it is not well-calibrated and theoretically not proved.

APPLICATION OF THE NEWLY DEVELOPED IMPERFECTION IN INTERACTION BUCKLING RESISTANCE

PREVIOUS DESIGN PROPSALS – EUROCODE APPROACH

Global buckling reduction factor:

$$\chi = \frac{1}{\phi + \sqrt{(\phi^2 - \lambda^2)}} \qquad \phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] \qquad \bar{\lambda}_{g\,class4} = \beta\,\bar{\lambda}_g = \sqrt{\frac{A_{eff}}{A}}\,\bar{\lambda}_g$$

Local buckling reduction factor:

$$A_{c,eff} = \rho\, A_c \qquad \rho = \begin{cases} \rho = 1, & \bar{\lambda}_p < 0.673 \\ \rho = \dfrac{\bar{\lambda}_p - 0.005\left(3 + \psi\right)}{\bar{\lambda}_p^2} \leq 1, & \bar{\lambda}_p \geq 0.673 \end{cases}$$

Interaction buckling resistance for slender sections:

$$N_{b,Rd} = \frac{\chi A_{eff} f_y}{\gamma_{M1}} = \frac{\chi \rho A f_y}{\gamma_{M1}}$$

Oversimplified neglecting the nonlinear combined effect of interaction.

PREVIOUS DESIGN PROPSALS - LITERATURE

Schillo

Equivalent local imperfection (e_p) to account for loss of stiffness due to local buckling.

$$ep = s\left[\left(\frac{1}{\chi_A} - 1\right) + \frac{1-\psi}{1+\psi}\left(\frac{1}{\chi_W} - 1\right)\right]$$

$$\eta = \alpha\left(\bar{\lambda}_{gs} - 0.2\right) + \left(e_L + e_p\right).\frac{A}{W}$$

$$\phi = \sqrt{\frac{1}{k_e}}.0.5\left[k_e + \eta.k_e + \bar{\lambda}_{gs}^2\right]$$

$$\chi_{gs} = \left[\frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}_{gs}^2}}\right]$$

Kuhlmann

Upgrade from “b” curve to “a” curve.

Modification of global slenderness considering the local slenderness.

$$\bar{\lambda}_{GL} = \sqrt{\frac{N_{Rk}}{N_{cr}}} = \sqrt{\frac{A\,f_y}{\pi^2\,\frac{EI}{L_{cr}^2}}}$$

$$\beta = \frac{i}{i_{eff}}.\left[1 - 0.5\,\chi_a\,\left(1 - 0.6.\sqrt{\rho_p}\right)\right]$$

$$\bar{\lambda}_{int} = \beta\,.\,\bar{\lambda}_{GL}$$

$$N_{Rd} = \frac{\chi A_{eff} f_y}{\gamma_1}$$

Young

Direct strength method (DSM) for welded box sections

$$P_{nl} = \begin{cases} P_{ne} \\ \left(1 - 0.2\left(\frac{P_{crl}}{P_{ne}}\right)^{0.55}\right)\left(\frac{P_{crl}}{P_{ne}}\right)^{0.55} P_{ne} \end{cases}$$

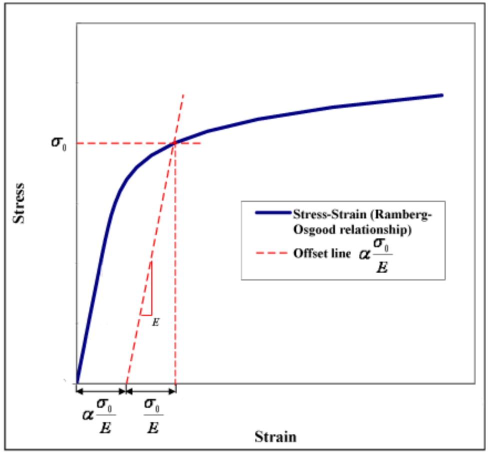
P_{crl} is the elastic local buckling load by finite elements Method or finite strip method

P_{ne} is the nominal column design load according to EC3
with appropriate buckling curve.

MATERIAL MODEL

S500 – S960

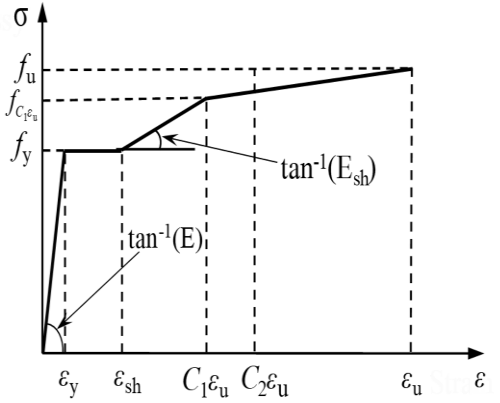
- the numerical model will utilize Ramberg-Osgood material model:
- $\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{f_y}\right)^{1/n}$, where
- $n = \frac{\log\left(\frac{\sigma y}{\sigma y}\right)}{\log\left(\frac{\varepsilon u}{\varepsilon u}\right)}$



S235 – S460

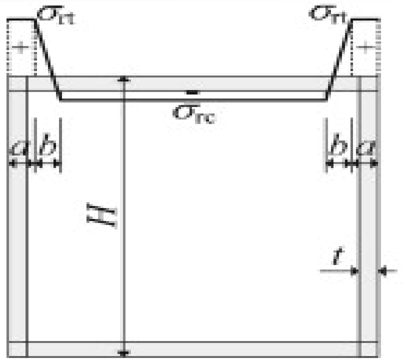
linear elastic – plastic model with strain hardening

	S235	S355	S460
f_y	235	355	460
f_u	360	510	540
ε_{sh}	0.010	0.015	0.030
ε_u	0.208	0.182	0.089
C_1	0.287	0.310	0.505
C_2	0.430	0.448	0.604
E_{sh}	1578	2310	3407
$C_1 \cdot \varepsilon_u$	0.060	0.057	0.045
$f_{C1\varepsilon u}$	313	451	510

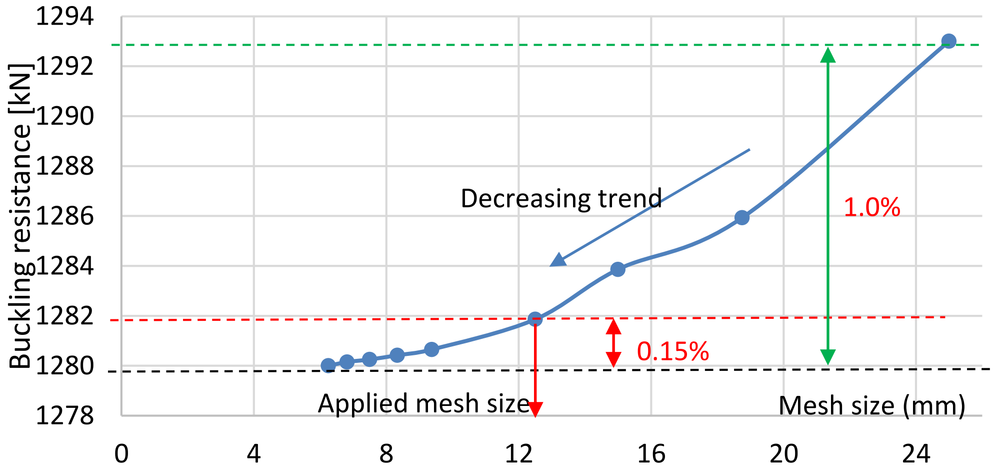


RESIDUAL STRESSES AND MESH SENSITIVITY

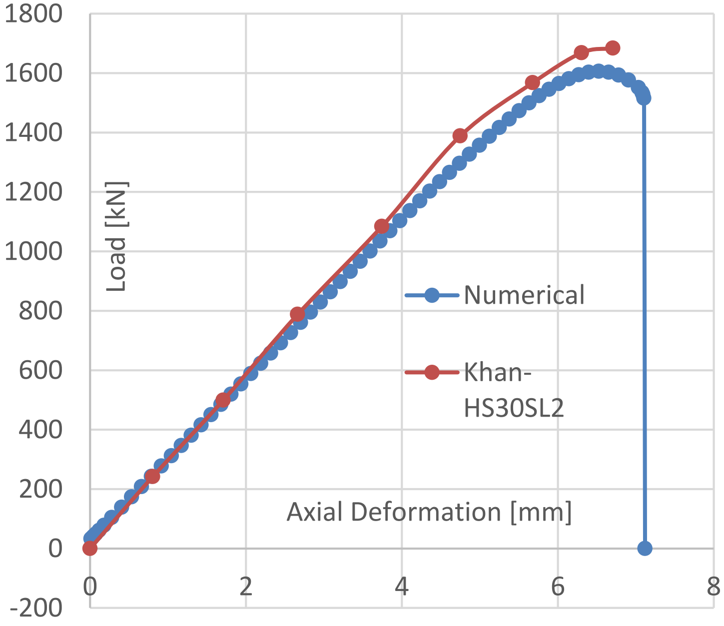
The distributions of residual stress for welded sections are shown in the figure, where '+'represents tensile stress and'−'represents compressive stress according to ECCS with the f_y as yield stress and 0.13*$355MPa$ as compressive stress for HSS and 0.13*f_y for NSS.



Mesh size of 12 mm was used

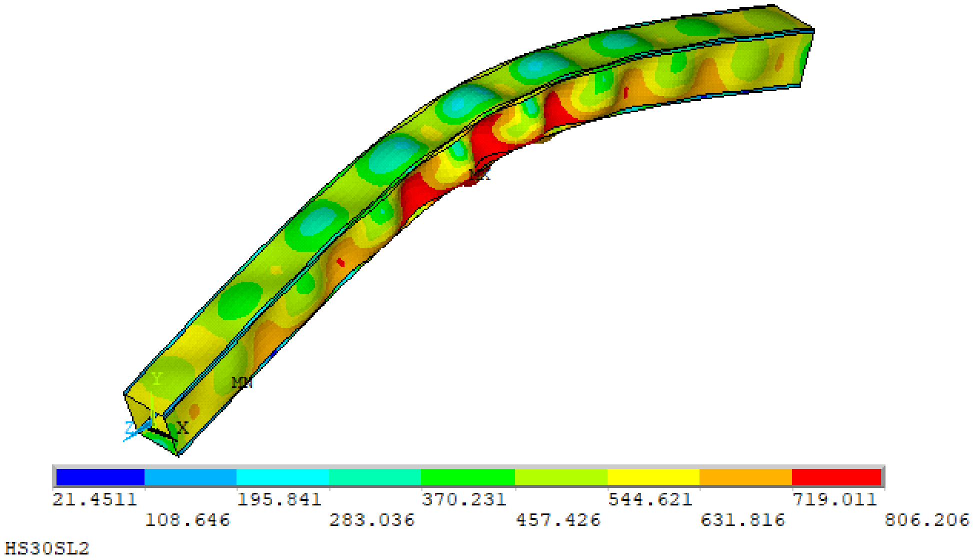


MODEL VALIDATION- INTERACTION BUCKLING



S700 150X150X4.9 mm
L=2512 mm

Validation with L/1000 global imperfection
Residual stress 0.13*355 MPa
Actual local imperfection b/516 mm acc. to Annex B curve



Model Validation- Interaction buckling

Schillo

Uncontrolled Eccentricity

Khan

Steel grade	λ_g	λ_p	b (mm)	h (mm)	t (mm)	L (mm)	f_y (MPa)	f_u (MPa)	$F_{u,exp}$ (kN)	$F_{u,num}$ (kN)	$\frac{F_{u,num}}{F_{u,exp}}$
S500	0.33	1.06	159.75	159.5	4.1	1599	562	640	880.3	948	1.08
S500	0.37	1.07	160	159.25	4	1800	562	640	883.9	925	1.05
S500	0.40	1.08	160	159	4	2000	562	640	858.2	899	1.05
S500	0.44	1.08	159.25	159.25	4	2198	562	640	828.9	889	1.07
S960	0.23	1.17	136	136	4.2	728	980	1024	1400.4	1383	0.99
S960	0.42	1.24	137	137	4	1299	980	1024	1390.5	1223	0.88
S960	0.45	1.23	137	137	4	1399	980	1024	1396.6	1230	0.88
S700	0.28	1.22	199	199	4.9	1512	762	819	1733	1735	1.00
S700	0.45	0.90	149	149	4.9	1512	762	819	1800	1698	0.94
S700	0.57	0.74	125	125	4.9	1512	762	819	1659	1593	0.96
S700	0.45	1.22	199	199	4.9	2512	762	819	1598	1626	1.02
S700	0.72	0.9	150	150	4.9	2512	762	819	1688	1605	0.96

New Numerical parametric Study – Interaction

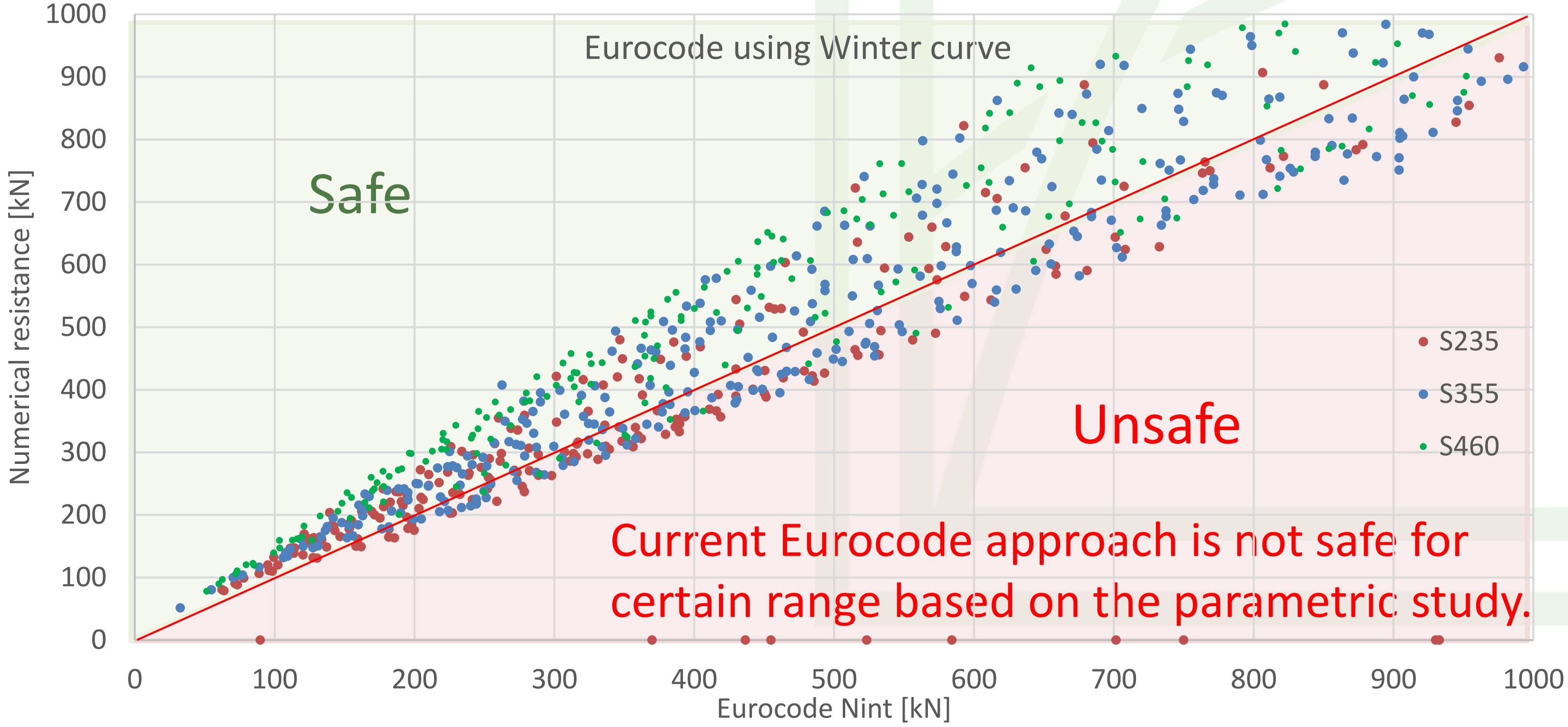
Around 2000 numerical tests were done with these ranges of variables to conduct the parametric study.

- Plate slenderness ranges from 0.7 to 3.
- Global slenderness ranges from 0.1 to 2.5
- Section width ranges from 200 to 450 mm, 50mm increment.
- Length ranges from L=700 to 20000mm
- Plate thicknesses – 2-11 mm with 0.25 mm increment
- Steel grades are S235, S355 , S460, S500 , S690 , S960.

EUROCODE3 RESISTANCE COMPARED TO NUMERICAL RESISTANCE

using Winter curve

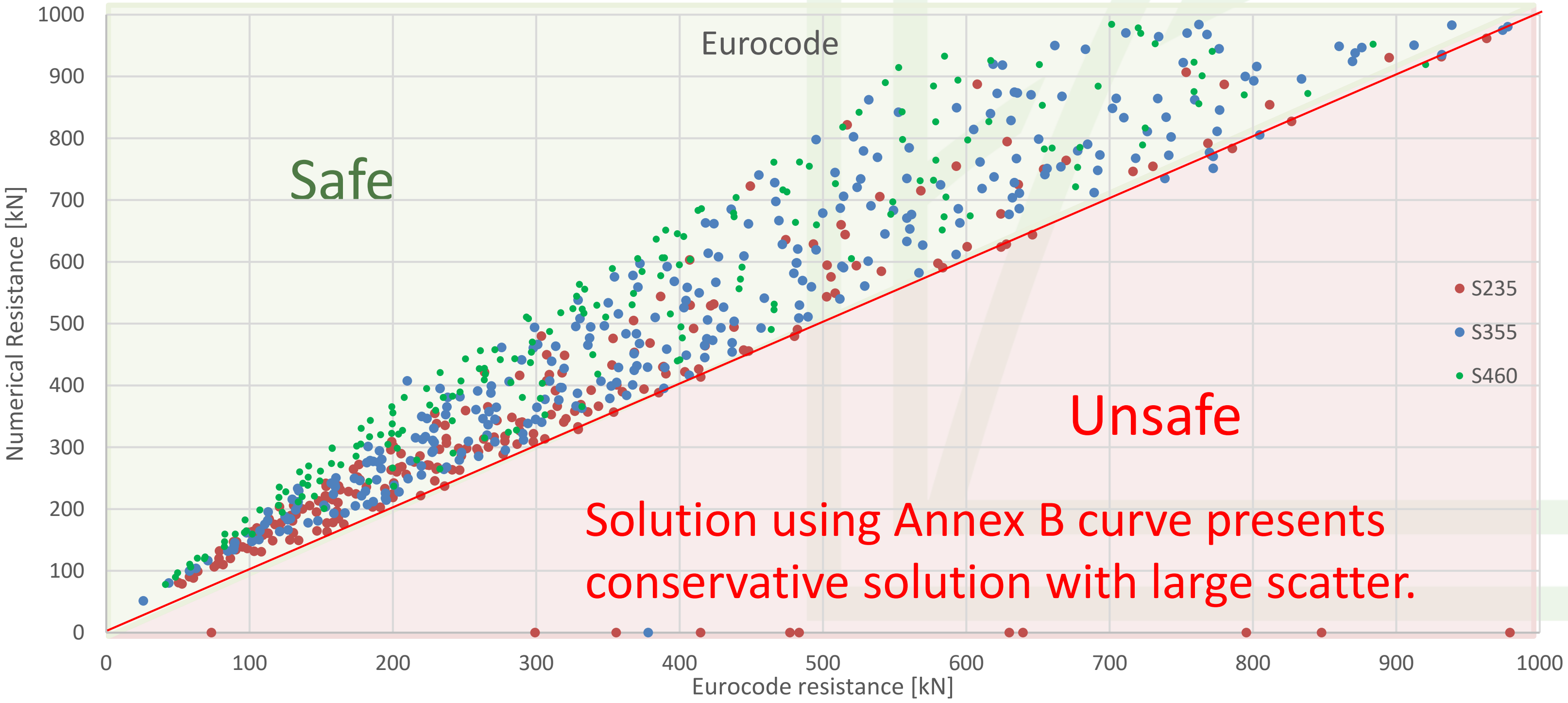
$$\bar{\lambda} = \sqrt{\frac{A_{eff} f_y}{N_{cr}}}$$



EUROCODE3 RESISTANCE COMPARED TO NUMERICAL RESISTANCE

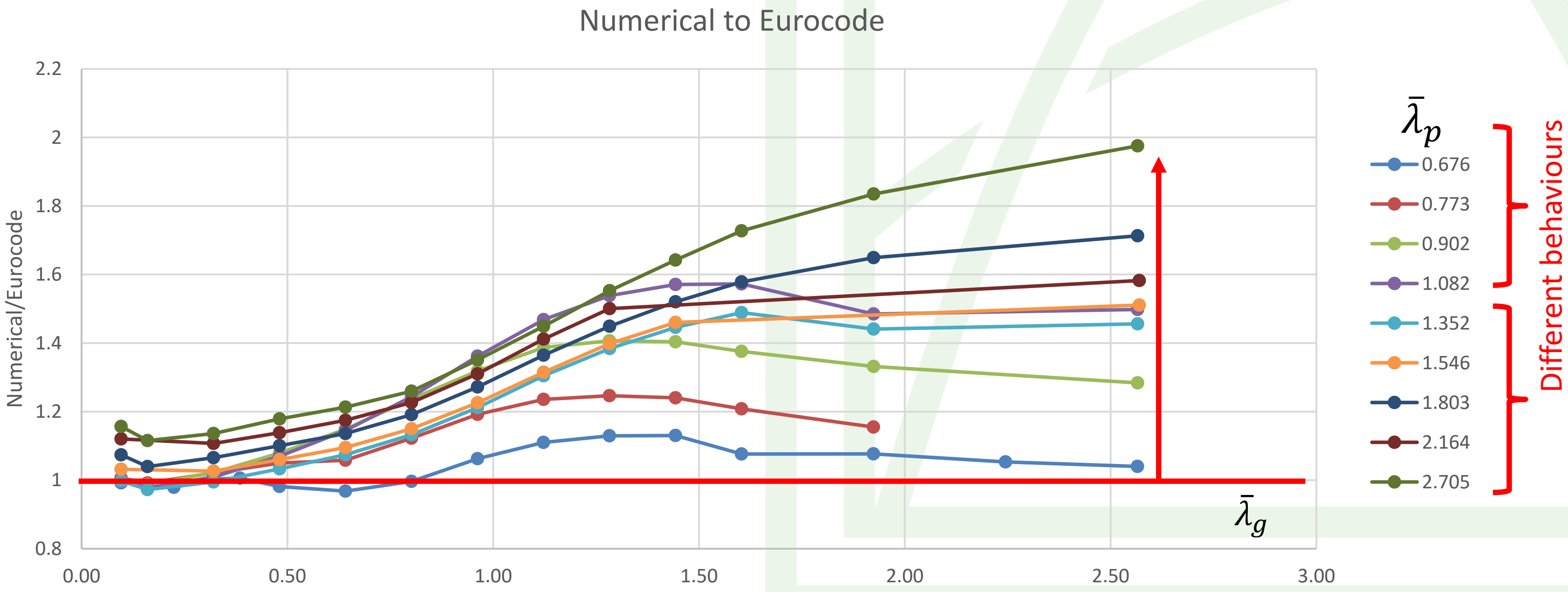
using Annex B curve

$$\bar{\lambda} = \sqrt{\frac{A_{eff} f_y}{N_{cr}}}$$



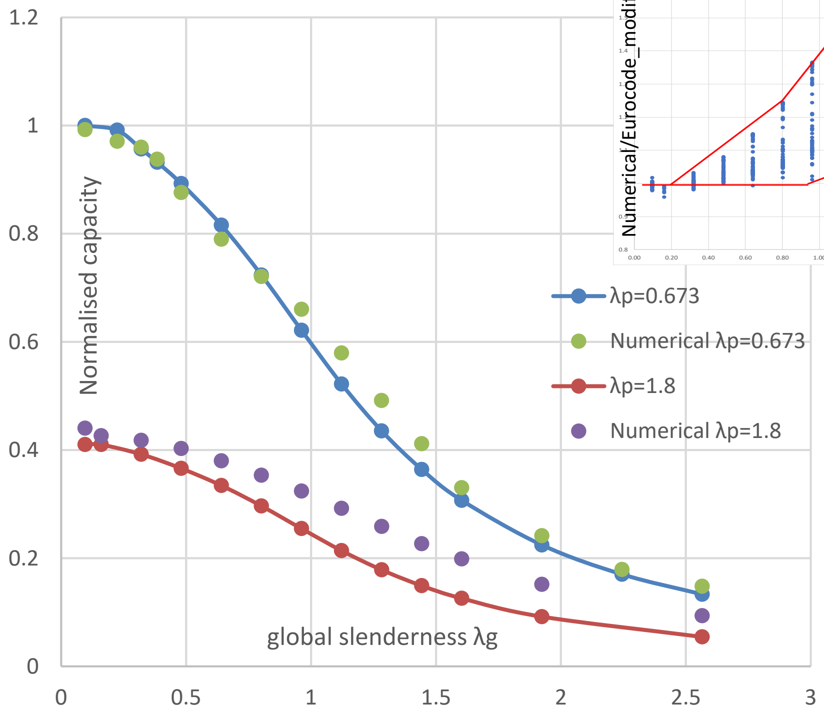
Solution using Annex B curve presents conservative solution with large scatter.

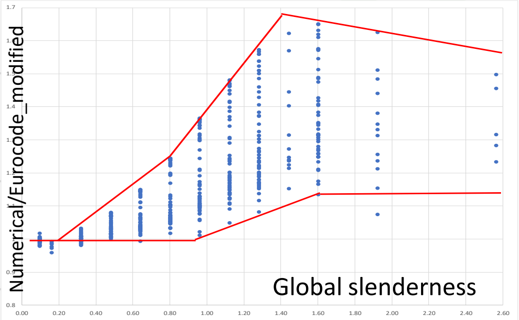
Effect of global and local slenderness

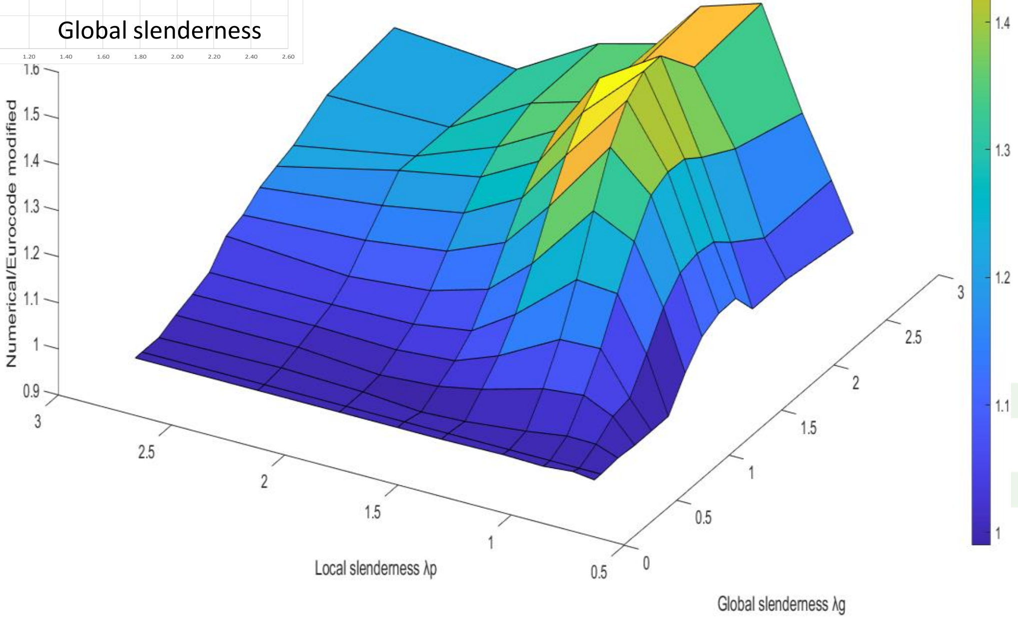


Resistance difference is slenderness dependent improved design method is needed → both global and local slenderness has impact with clear trend.

Effect of global and local slenderness







Design Proposal:

- $$Factor_{max} = \begin{cases} 1, & \bar{\lambda}_p \leq 0.67 \\ 1 + (\bar{\lambda}_p - 0.67) * \frac{0.45}{0.33}, & 0.67 < \bar{\lambda}_p \leq 1 \\ 1.45, & \bar{\lambda}_p > 1 \end{cases}$$

Calculating the local buckling factor and maximum value of the modification factor.

- $$Factor_{mod} = \begin{cases} 1, & \bar{\lambda}_g < 0.4 \\ 1 + (\bar{\lambda}_g - 0.4) * (Factor_{max} - 1), & 0.4 \leq \bar{\lambda}_g < 1.4 \\ Factor_{max}, & \bar{\lambda}_p \geq 1.4 \end{cases}$$

Calculation of the interaction factor.

my contribution

- $$N_{int} = \boxed{Factor_{mod}}\, \chi_b . A_{eff} . f_y$$

Calculation of the interaction resistance.

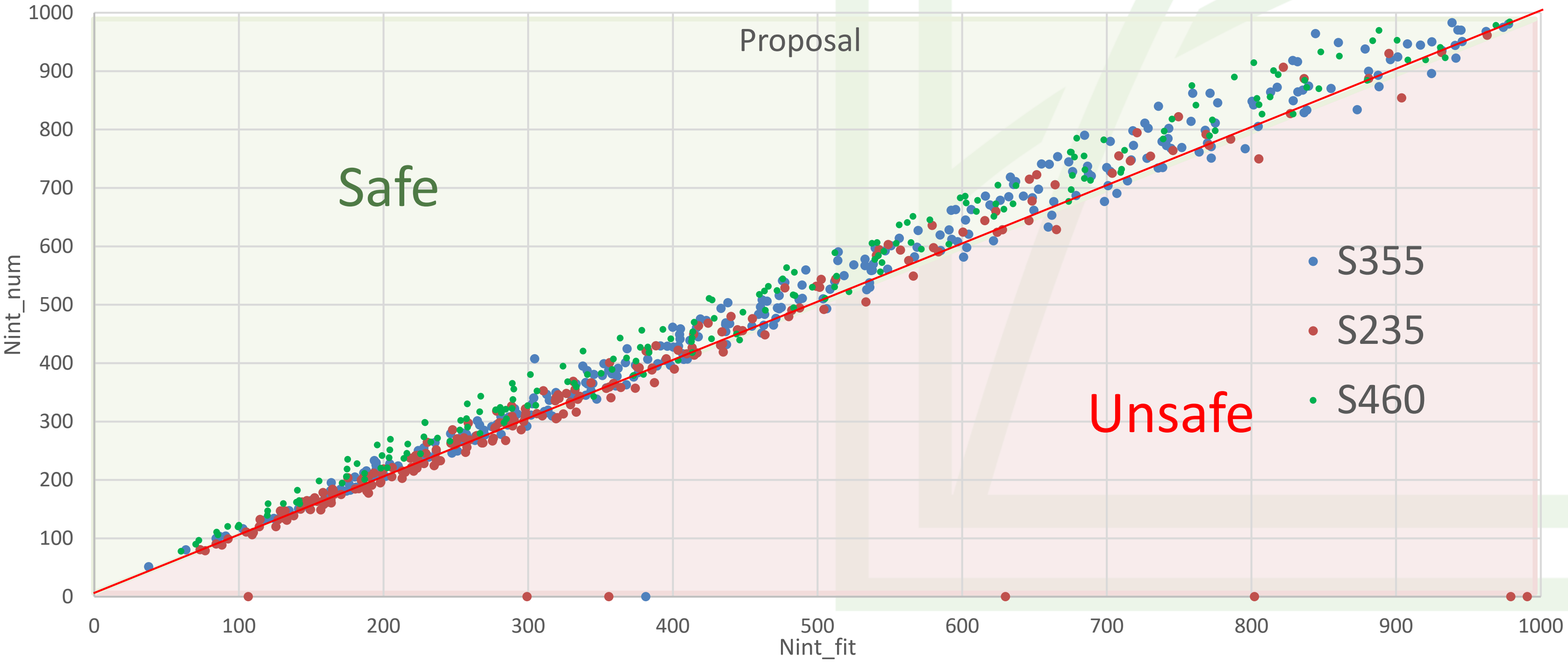
easy-to-apply design rule with clear physical background and calibrated to GMNIA results.

Global reduction factor (curve b)

Effective area based on Annex B curve

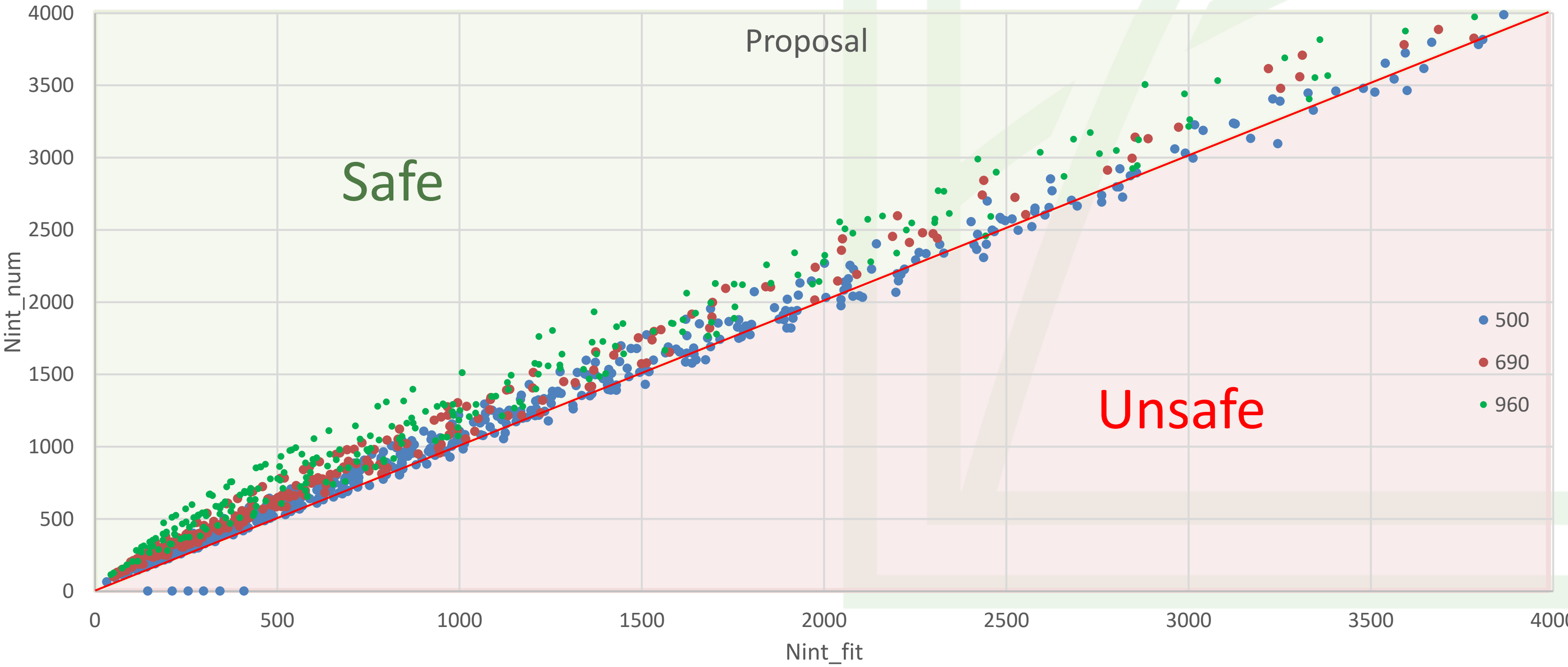
FIT TO NUMERICAL RESULTS - NSS

The proposed fit is very reliable with close values to numerical results



FIT TO NUMERICAL RESULTS - HSS

The proposed fit is very reliable with close values to numerical results



Conclusions

- Accurate and reliable geometric imperfection is determined to achieve the local buckling resistance of box-sections.
- Numerical paramteric study is executed with this imperfection to determine accurate global and local interaction resistance.
- Clear trend is found on the resistance ratio and global / local slenderness ratios in case of interaction buckling.
- Enhanced and simple interaction design equation is developed to improve the Eurocode based design approach.
- The proposed method provides safe results compared to the GMNIA analyses.

PUBLISHED WORKS:

- M. Radwan, B. Kövesdi: Local plate buckling type imperfections for NSS and HSS welded box-section columns, Structures, Volume 34, 2021, Pages 2628-2643,ISSN 2352-0124, https://doi.org/10.1016/j.istruc.2021.09.011. IF: 2.983

- M. Radwan, B. Kövesdi: “Equivalent Geometric Imperfections for Local Buckling of Slender Box-section Columns”, Periodica Polytechnica Civil Engineering, 2021. https://doi.org/10.3311/PPci.18545. IF: 1.361

- M. Radwan, B. Kövesdi: “Enhanced design method for global and local buckling interaction of welded box-section columns”, Journal of Constructional Steel Research 2022;194:107334. https://doi.org/10.1016/j.jcsr.2022.107334. IF: 3.646

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- [4]“References,” in Designers’ Guide to EN 1993-1-1 Eurocode 3: Design of Steel Structures, 0 vols., Thomas Telford Publishing, 2005, pp. 161–162.
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THANK YOU

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