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Work package 2: Structural performance of steel members
Deliverable 2.5: Recommendations for the use of DSM

Petr Hradil, Asko Tajla
VTT, Technical Research Centre of Finland

Marina Bock, Martí Garriga, Esther Real, Enrique Mirambell
Departament d'Enginyeria de la Construcció,
Universitat Politècnica de Catalunya

Table of contents

Local buckling

BOCK, M., GARRIGA, M., REAL, E., MIRAMBELL, E., Recommendations for the use of DSM: Local Buckling

Local-overall interaction

HRADIL., P., TALJA, A., VTT-R-03253-13: Recommendations for the use of Direct Strength Method



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Work package 2.5. Recommendations for the use of DSM: Local Buckling

Marina Bock

Esther Real

Enrique Mirambell

Marti Garriga

Departament d'Enginyeria de la Construcció,
Universitat Politècnica de Catalunya



UNIVERSITAT POLITÈCNICA
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C/ Jordi Girona, 31
08034-Barcelona
España

Project leader: Esther Real

Report authors: Bock, M., Real, E., Mirambell, E.,
Garriga, M.

Contents

1. Introduction.....	4
1.1 Target.....	4
2. The Direct Strength Method.....	5
2.1 Carbon steel.....	5
2.2 Stainless steel.....	5
2.3 CUFSM	5
2.3.1 Introduction	5
2.3.2 Section modeling and features	7
2.4 Cross section resistance by EN 1993	8
3. Parametric study database	10
3.1 Cross sections.....	10
3.2 Materials.....	11
4. Parametric study. Results from stub column tests	12
4.1 Hollow sections (SHS and RHS)	12
4.2 I-sections.....	15
4.3 Channels	17
5. Conclusions.....	19
6. References.....	20
Annex A. SHS/RHS sections results	21
Annex B . Channel sections results	32
Annex C. I-sections results	39

1. Introduction

If the reduction of the plate width is the fundamental concept behind the effective width method, then accurate member stability is the fundamental idea behind the Direct Strength Method. The Direct Strength Method (Schafer, 2008) is predicated upon the idea that if an engineer determines all the elastic instabilities for the gross section (local, distortional and global buckling) and also determines the moment that causes the section to yield, then the strength can be directly determined.

The method is essentially an extension of the use of column curves for global buckling, but with application to local and distortional buckling instabilities and appropriate consideration of post-buckling reserve and interaction in the modes. This method has been pioneered by Dr. Schafer and his co-workers from John Hopkins University in the United States. It has been somewhat inspired by outstanding research performed by Dr. Hancock into distortional buckling of rack-post sections. The Direct Strength Method can be alternatively used in the calculation of cold-formed sections in the specifications from the United States, Australia and New Zealand. It has an empirical basis, which is proven straightforward and reliable enough compared to the effective width method.

The method is applicable to the following calculations:

- Column and beam design
- Flexural, torsional, or torsional-flexural buckling when applicable
- Local buckling
- Distortional buckling

Empirically-based, the method consists of defining a non-dimensional slenderness, which is a function of the critical buckling force and the yield moment. It is worth pointing out that the relevant buckling load should be obtained by numerical calculations.

Attempts for using the Direct Strength Method in stainless steel design are less frequent though. The empirical basis of the formulation avoids a direct transition from carbon to stainless steel without performing new regression analysis. Some attempts for obtaining equations for distortional-buckling related formulae for stainless steel cross-sections have been proposed by Lecce and Rasmussen (2006) and Becque et al. (2008).

1.1 Target

The study of local buckling phenomenon using cross-section classification involves the assessment of class 3 limit, which defines the boundary between slender sections, that are those susceptible to local buckling (class 4), and stocky sections. And the cross-section resistance is determined by the concept of effective widths.

This study will be tackled as a continuation of the one presented in WP2.4 Parametric study and recommendations for local buckling (Bock et al., 2013), were a comparison between the use of EN1993-1-4 (2006) for stainless steel, EN1993-1-1 (2005) for carbon steel and the Gardner and Theofanous (2008) proposals and CSM for determining the cross section resistance in fully compressed internal element was presented.

The main objective is to study the applicability of the Direct Strength Method to the same cross-sections and the same materials and compare the ultimate resistance obtained with different methods.

2. The Direct Strength Method

2.1 Carbon steel

The Direct Strength Method was initially designed for carbon steel members; its formulation shall be used as a reference for the purpose of this project. It can be found at the Appendix 1 of the "Specifications for the Design of Cold-Formed Steel Structural Members" by the AISI (2007). This report is focused only on the cross-section resistance.

Equations 1 to 3 are the ones applied to the specimens to obtain their strength as defined in the Direct Strength Method Design Guide, AISI (2006).

for $\lambda_l \leq 0.776$

$$P_{nl} = P_y \quad (1)$$

for $\lambda_l > 0.776$

$$P_{nl} = \left[1 - 0.15 \left(\frac{P_{crl}}{P_y} \right)^{0.4} \right] \left(\frac{P_{crl}}{P_y} \right)^{0.4} P_y \quad (2)$$

Where $\lambda_l = \sqrt{P_y/P_{crl}}$ (3)

P_{nl} =nominal axial strength

P_y =AgFy

P_{cr} is the critical elastic buckling load

2.2 Stainless steel

The formulation used for stainless steel is the one proposed in Beque et al. (2008) (Equations 4 and 5).

$$P_{nl} = \begin{cases} P_y & \text{for } \lambda_l \leq 0.55 \\ \left(\frac{0.95}{\lambda_l} - \frac{0.22}{\lambda_l^2} \right) P_y & \text{for } \lambda_l > 0.55 \end{cases} \quad (4)$$

Where:

$$\lambda_l = \sqrt{\frac{P_y}{P_{cr}}} \quad (5)$$

2.3 CUFSM

2.3.1 Introduction

The DSM focuses on the correct determination of elastic buckling behavior instead of building an artificial concept as an effective cross-section, and requires the computation of the elastic local buckling stress.

Elastic buckling analysis of any sections geometry can be performed on CUFSM (Cornell University Finite Strip Method) which delivers the cross-section instabilities. Mechanics employed by the CUFSM are identical to the mechanics used to derive the plate bucking

coefficient "k" values in current use. A brief insight into the program is worth towards getting an overall idea of the direct strength method (Schafer, 2006).

The finite strip method is a variant of the finite element method which instead of modeling the member in a number of square elements it uses strips from side to side of the element as shown in figure 2.1.

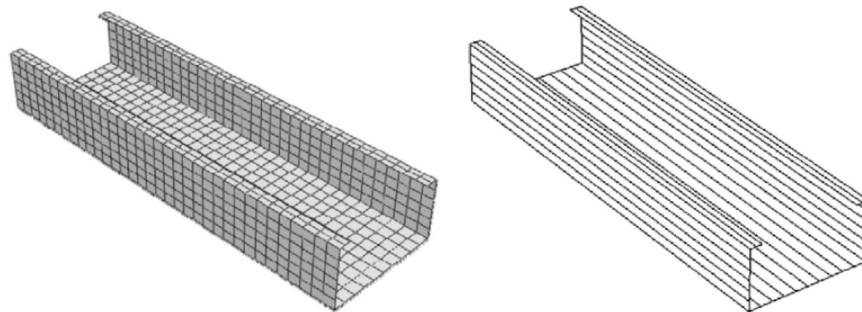


Figure 2.1: C section discretised in FEM and in FSM respectively. (Beregszaszi, 2011)

Nodal displacements employ sinusoidal functions characterized by a half-wavelength parameter initially undefined, that parameter governs the mode shapes and so it is crucial towards determining the elastic buckling instabilities.

A typical CUFSM analysis would provide a graphic like the one shown in figure 2.2. In the horizontal axis the half-wave length which governs the mode shape are presented and at the vertical axis we've got the load factor.

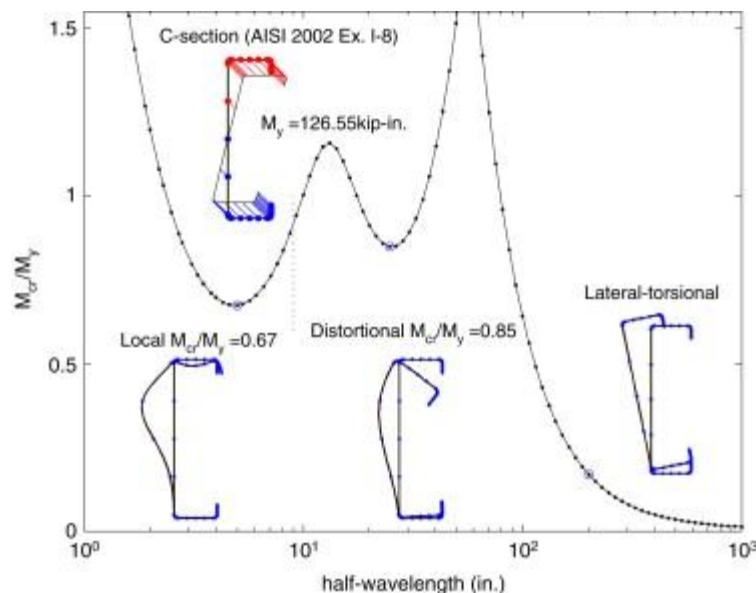


Figure 2.2: Semi-analytical finite strip solution of a C-section with lips in bending showing local, distortional and lateral-torsional buckling as well as the moment that causes first yield. (Schafer, 2008).

The curve is characterized by three minima, each of them corresponding to a different mode of instability (local bucking, distortional bucking and LTB).

2.3.2 Section modeling and features

The first step in determining the local instabilities is to build a proper strip model of the RHS, SHS sections, Channels and I sections with round corners. As suggested in (Beregszaszi, 2011) 90 degrees round corners have been approximated as 4 narrow strips. 4 strips will be used too for the webs.

To ensure that section modelling is refined enough to deliver feasible solutions several sections with double the previous number of elements defined have been analysed. The conclusions are that for very stocky cross-sections results of load factor vary by at most 0.03 units, for slender sections results do not change at all. Even more, those very stocky sections would all fail by strength criteria instead of instability. Therefore it can be concluded that the model of 32 elements has enough precision. Note that this model has been found to have a relative error characterized over all SHS and RHS specimens analysed by a mean 0.48 % underestimation of the actual gross section and a standard deviation of 0.0025. The error of Channels is characterized by a mean of 3.4% overestimation and a standard deviation of 0.0161 and the one of I sections has a mean of 1.6% overestimation and 0.0033 standard deviation. It is worth mentioning that errors grow slightly as slenderness decreases, specially for low values of slenderness that lead to section squashing instead of buckling, hence not relevant to our analysis. Figure 2.3 shows how a model of a SHS 100x100x2x4 looks like on CUFSM.

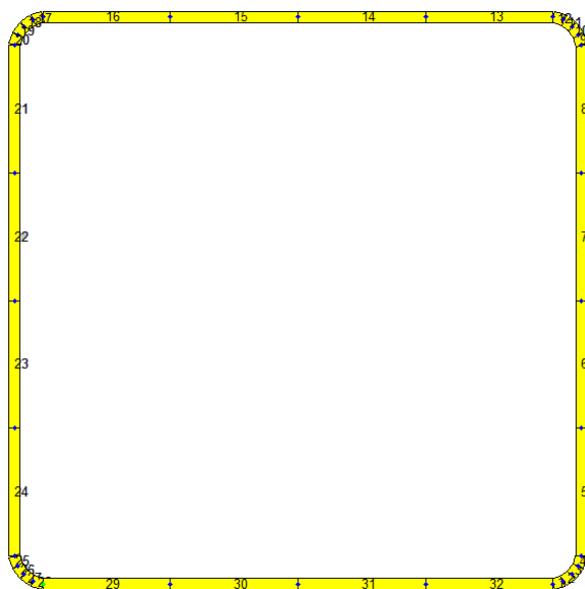


Figure 2.3: Model on CUFSM of a SHS 100x100x2x4

All the sections analysed have been found to have two minima corresponding to local and global buckling. Sections analysed do not suffer torsional buckling under axial or pure bending. Other types of sections such as Channels with lips do suffer from distortional buckling.

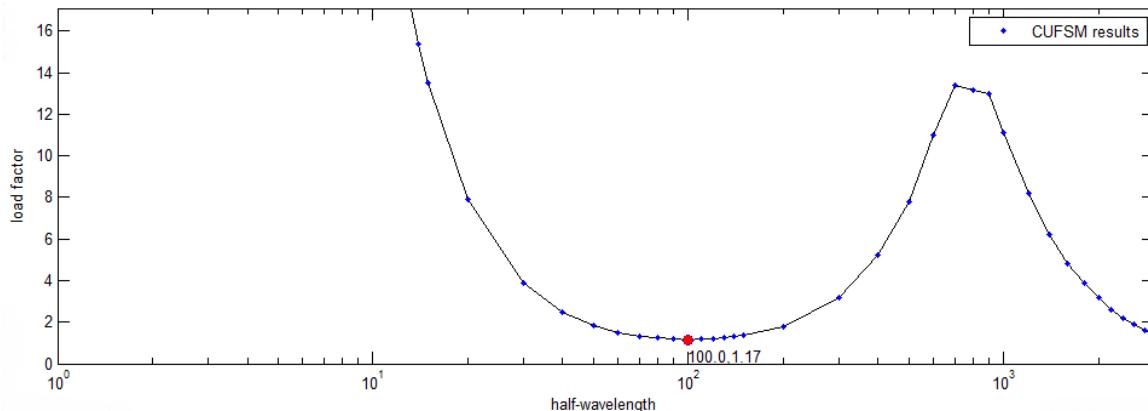


Figure 2.4: Load factor – half-wavelength graph obtained through CUFSM of a 100x100x2 mm SHS. Half-wavelength in mm.

Through many analyses it has been found that the half-wavelength at which members suffer local buckling is close to its largest dimension. For the 100X100X2mm SHS (figures 2.3 and 2.4) the member suffers local buckling at a half-wavelength of 100 mm. Figure 2.5 shows an overall view of a SHS local buckling.

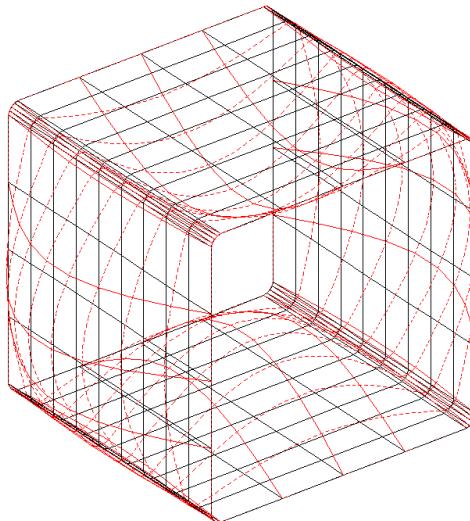


Figure 2.5: 3D figure of the local buckling of a 140x140x2 SHS, deformations exaggerated 40 times

2.4 Cross section resistance by EN 1993

As it has been said before, the results of the resistance obtained by using the DSM will be compared with the ones obtained using the cross-section classification and the effective width concept for class 4 sections (see (Bock et al., 2013)).

Elements in compression might be calculated as follows:

$$N_{c,Rd} = \sigma_{0.2} \cdot A_g \quad \text{For class 1, 2 and 3 sections} \quad (6)$$

$$N_{c,Rd} = \sigma_{0.2} \cdot \rho \cdot A_g = \sigma_{0.2} \cdot A_{eff} \quad \text{For class 4 sections} \quad (7)$$

Where A_g is the gross-cross section and A_{eff} is the effective-cross section.

It is important to point out that the gradually strain hardening of stainless steel is not considered in this method which never assumes stresses above the proof stress. In addition, class 1 to 3 sections fully compressed, as well as class 1 and 2 subjected to bending, are treated equally providing a clear underprediction of their cross-section resistance.

Different proposals are presented for the class section limits in EN1993-1-4 (2006) for stainless steel, EN1993-1-1 (2005) for carbon steel and the Gardner and Theofanous (2008) proposal also for stainless steel for members in compression, and also, different expressions for the reduction function ρ . The three expressions will be compared with the DSM results.

3. Parametric study database

3.1 Cross sections

The study will be focused on SHS, RHS, I-sections and Channels (without lips) subjected to uniform compression and therefore, the results from WP2.4 Parametric study and recommendations for local buckling (Bock et al., 2013) could be compared.

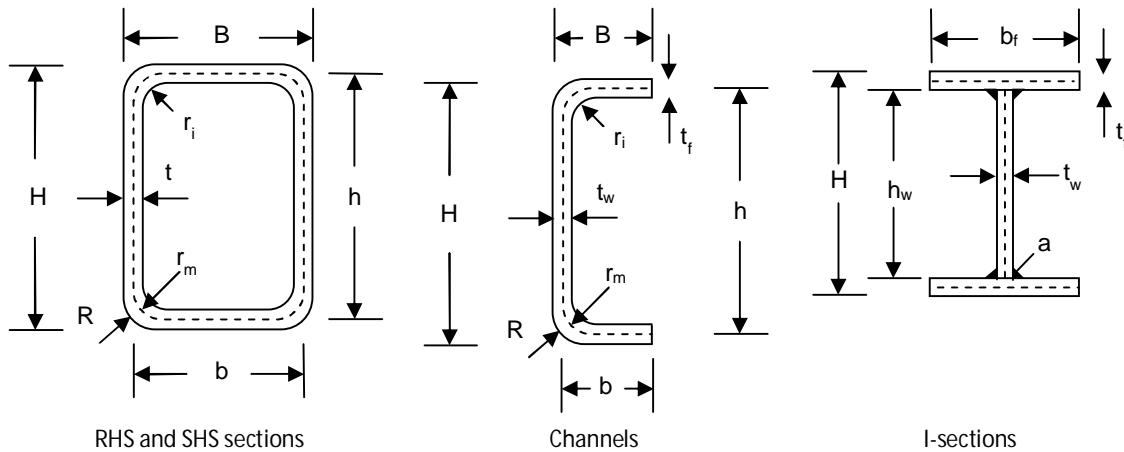


Figure 3.1 Definition of symbols for considered cross-sections

The cross-section dimensions considered are specified as follows according to nomenclature defined in figure 3.1:

<u>SHS:</u>	$h \times b \times t \times r_i$	(S11): 90x90x2x4
	(S1): 40x40x2x4	(S12): 100x100x2x4
	(S2): 40x40x3x4*	(S13): 100x100x2.25x4.5
	(S4): 40x40x3x6	(S14): 100x100x2.5x5
	(S5): 55x55x1.5x3.5	(S15): 100x100x3x4*
	(S6): 65x65x1.5x3.5	(S16): 100x100x3x6
	(S7): 65x65x1.75x3.5	(S17): 110x110x2x4
	(S8): 70x70x1.5x3.5	(S18): 120x120x2x4
	(S9): 70x70x1.75x3.5	(S19): 130x130x2x4
	(S10): 90x90x1.75x3.5	(S19): 140x140x2x4

* $r_i < 2t$

<u>RHS:</u>	(R1): 80x60x1.75x3.5	(R4): 80x60x3x4
	(R2): 80x60x2x4	(R5): 80x60x3x
	(R3): 80x60x2.25x4.5	

<u>I-sections:</u>	$b_f \times h_w \times t_f \times t_w$	(I7): 80x40x3.5x3.5
	(I1): 100x50x3x3	(I8): 70x40x3.25x3.5
	(I2): 100x50x2.5x3	(I9): 70x40x3x3.5
	(I3): 100x50x2x3	(I10): 70x40x3.75x4
	(I4): 80x40x3x3	(I11): 100x80x5.5x4
	(I5): 80x40x2.75x3	(I12): 100x80x6x4
	(I6): 80x40x3.25x3	

<u>Channels:</u>	$h_{wxb_r} \times t_{xr_i}$	(C7): 100x50x3x6
	(C1): 40x30x2x4	(C8): 100x50x4x8
	(C2): 40x30x3x6	(C9): 120x60x3x6
	(C3): 60x30x3x6	(C10): 140x60x5x10
	(C4): 60x35x3x6	(C11): 160x70x5x10
	(C5): 80x40x3.25x6.5	
	(C6): 80x40x3x6	

The length of all the specimens have been set to keep three times the largest plate that makes up the cross-section.

Total of numerical models: (19SHS + 5RHS + 12I-section + 11Channels) x 12materials = 564

3.2 Materials

The materials analyzed in this study are austenitics and ferritics stainless steels and carbon steel. Specimens with different material properties have been analyzed for each type of steel. All specimens have the same yield strength but different ultimate tensile strength. The Young modulus is taken as 200,000 N/mm² for all specimens and the yield stress is taken as the stress at which the member suffers a proof strain of 0.2. The key parameters of the materials considered in this parametric study are presented in Table 3.1

Label	E_0	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u	ε_u	n	m	$\sigma_u / \sigma_{0.2}$	Assumed type of steel
M1	200	250	256	275	0.4	5	3	1.1	Austenitic
M3	200	250	262.2	300	0.4	5	3	1.2	Austenitic
M5	200	250	275	350	0.4	5	3	1.4	Austenitic
M7	200	250	300	450	0.4	5	3	1.8	Austenitic
M2	200	250	256	275	0.4	10	3	1.1	Ferritic
M4	200	250	262.2	300	0.4	10	3	1.2	Ferritic
M6	200	250	275	350	0.4	10	3	1.4	Ferritic
M8	200	250	300	450	0.4	10	3	1.8	Ferritic
C1	200	250	256	275	0.4	100	3	1.1	Carbon
C2	200	250	262.2	300	0.4	100	3	1.2	Carbon
C3	200	250	275	350	0.4	100	3	1.4	Carbon
C4	200	250	300	450	0.4	100	3	1.8	Carbon

Table 3.1 Material parameters considered in the parametric study

4. Parametric study. Results from stub column tests

The results from the parametric study are shown in this section where the results for the 3 different cross-sections are presented separately.

The numerical values of ultimate resistances calculated according different methods and numerical results are presented in Annex A-C.

4.1 Hollow sections (SHS and RHS)

The results obtained in the parametric study are shown in figure 4.1 where the sectional ultimate response ($N_{u,num}/A\cdot\sigma_{0,2}$) is plotted against the slenderness of the section calculated with the CUFSM. These results are compared with the proposed curves for the Direct Strength Method for carbon steel (eq. 1-3) and the ones for the Direct Strength Method for stainless steel (eq. 4,5).

The figure highlights the different response of the three materials studied: austenitics ($n=5$), ferritics ($n=10$) and carbon ($n=100$) with strain hardening. The main conclusions that can be drawn from figure 4.1 are:

- The DSM curve proposed for carbon steels fits very well the results for specimens with $n=100$ (carbon steels).
- For austenitics stainless steels ($n=5$), the curve proposed in the DSM is quite conservative for not very slender elements, and the limit of $\lambda_p=0.55$ seems also conservative.
- Ferritic stainless steels behave between carbon steels and austenitic stainless steels, so the curve for the DSM for stainless steels gives conservative results and could be improved for ferritics.

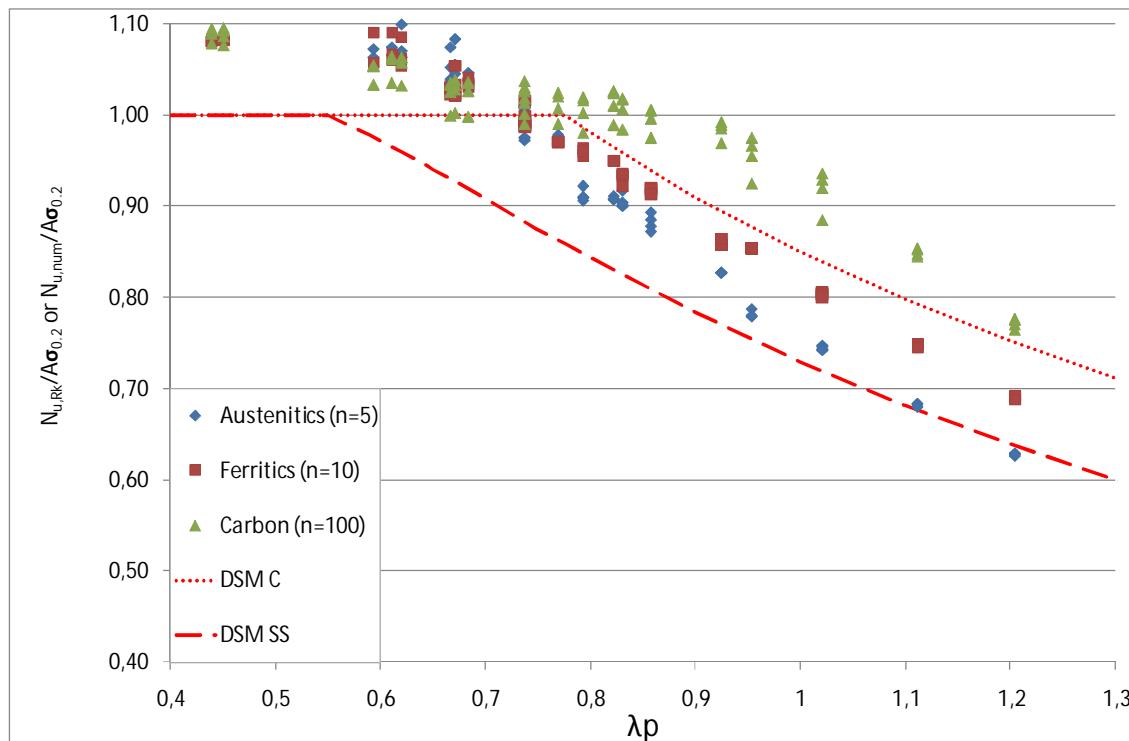


Figure 4.1 Assessment of the application of the DSM for fully compressed hollow sections (internal elements)

Figures 4.2-4.4 are presented with the aim of evaluating the differences when determining the ultimate theoretical load ($N_{u,Rk}$) according to different formulations.

These figures compare current EN1993-1-4, G&T proposal and DSM for stainless steels and EN1993-1-5 and DSM for carbon steels. In these cases, the slenderness in the X-axis is the one obtained for the overall section by using the CUFSM for all the cases, in order to have a good comparison. Although, the slenderness used to calculate the ultimate load with the EN 1993-1-4, G&T and the EN 1993-1-5 methods was the one determined with the flat part of the most slender part of the section sections ($\bar{b} = c$).

The following conclusions are worth to be mentioned:

- Current EN1993-1-4 provides safe results for all the materials but is more conservative for high n values.
- G&T proposal provides a good evaluation for the ultimate capacity but there are some values in slender sections with a ratio $N_{u,num}/N_{u,Rk}$ below the unity. The maximum overprediction has been up to a 4%. The proposed curve by G&T is not a suitable reduction factor for the austenitics considered in this parametric study (n=5). However, it is important to mention that this proposal was calibrated considering experimental results in which the average n value material was about 6. (see WP2.4)
- The DSM for stainless steels provides good results for austenitic and ferritic stainless steels (n=5, n=10) but is quite conservative for carbon steel (n=100) where the DSM proposed for carbon steel is better.
- The two analyzed methods for carbon steel, EN 1993-1-5 and DSM for carbon steels, do not provide good results for austenitics and ferritics and will over predict their ultimate capacity, so cannot be used when designing stainless steel, but are good for carbon steels.

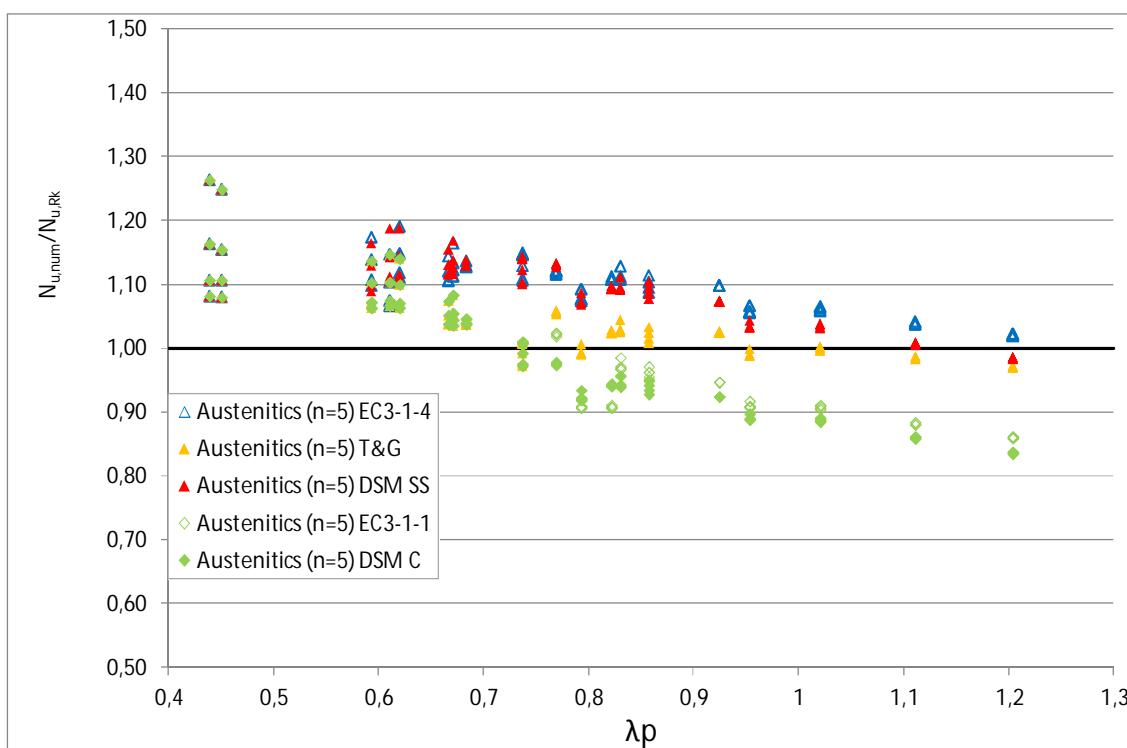
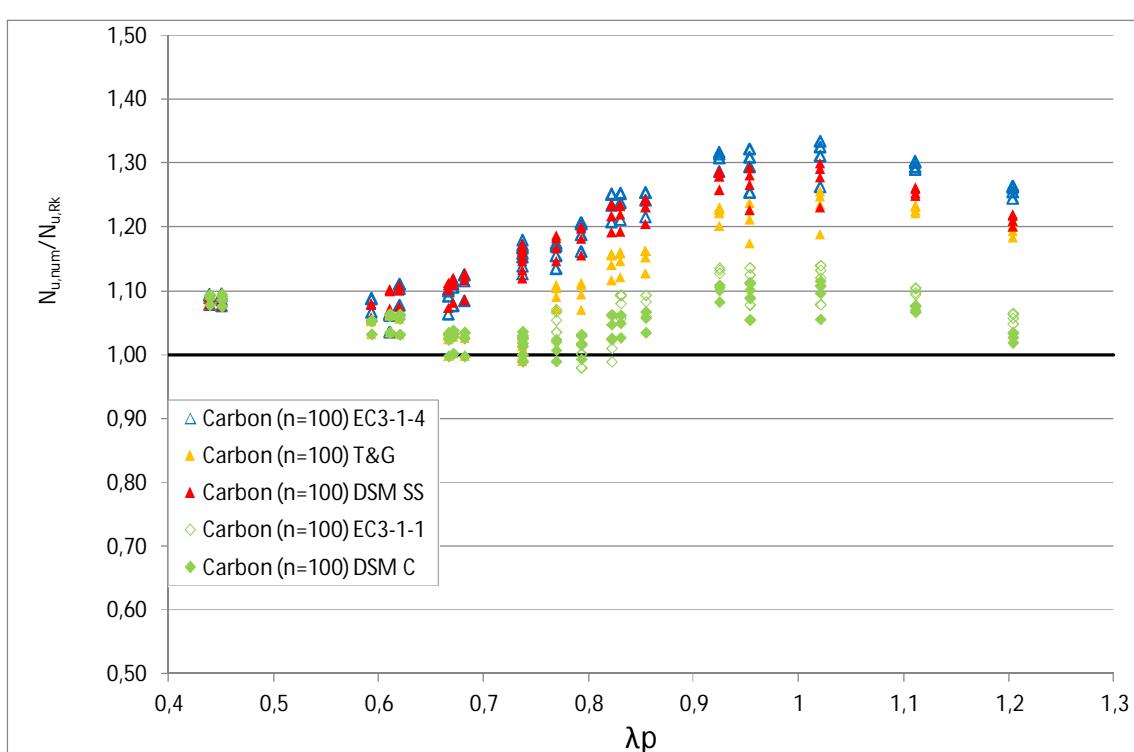
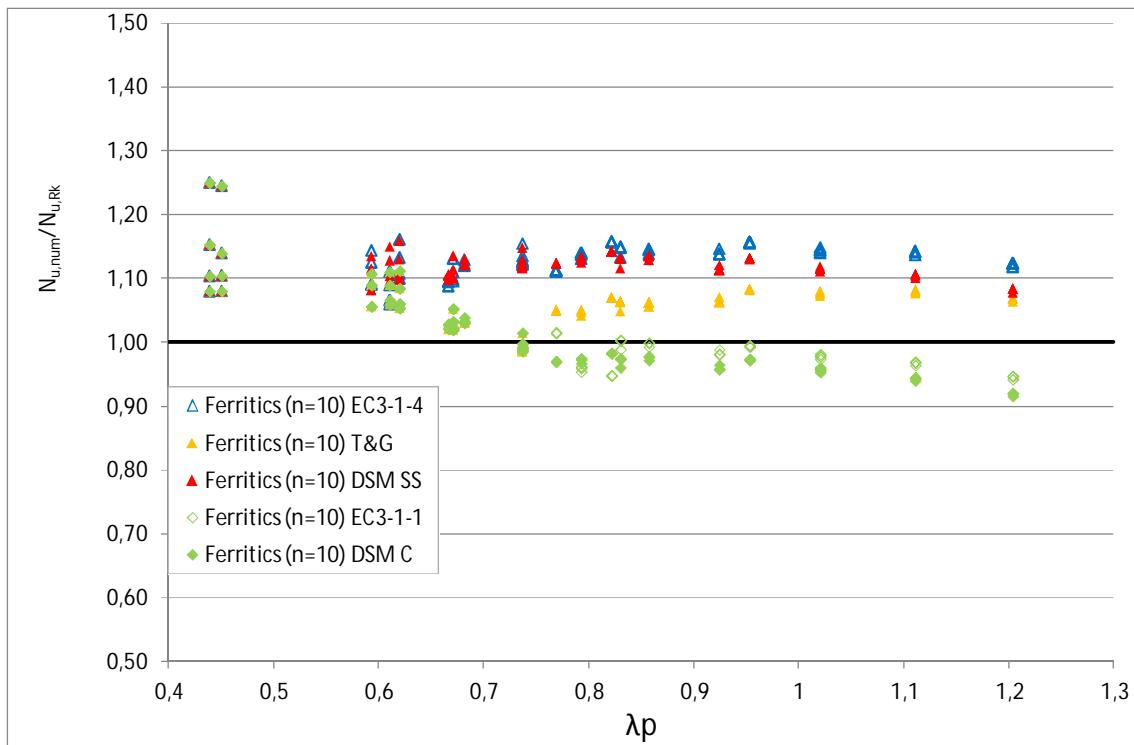


Figure 4.2 Comparison of analytical ultimate loads obtained according to the limits and reduction factors of EN1993-1-4, EN1993-1-5, G&T proposal and DSM for carbon steel and DSM for stainless steel. Austenitic stainless steel.



4.2 I-sections

The results obtained in the parametric study for I-sections are presented in figures 4.5 to 4.8 and similar conclusions to the SHS/RHS can be drawn.

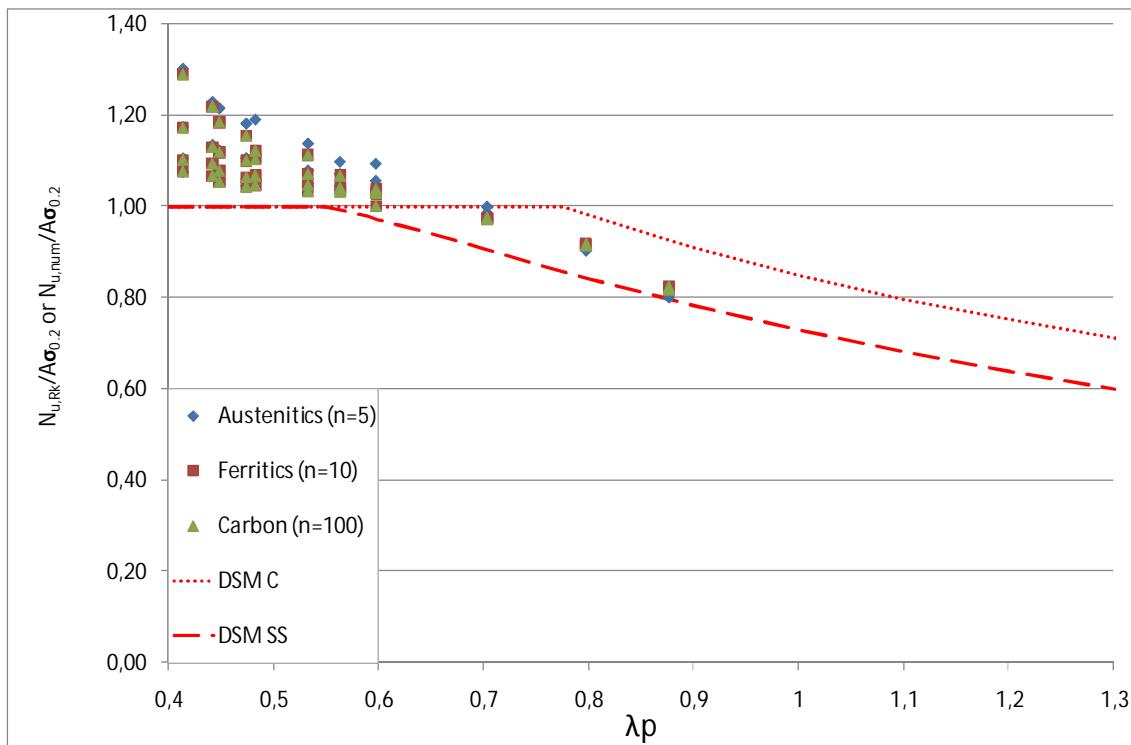


Figure 4.5 Assessment of the application of the DSM for fully compressed hollow sections (internal elements)

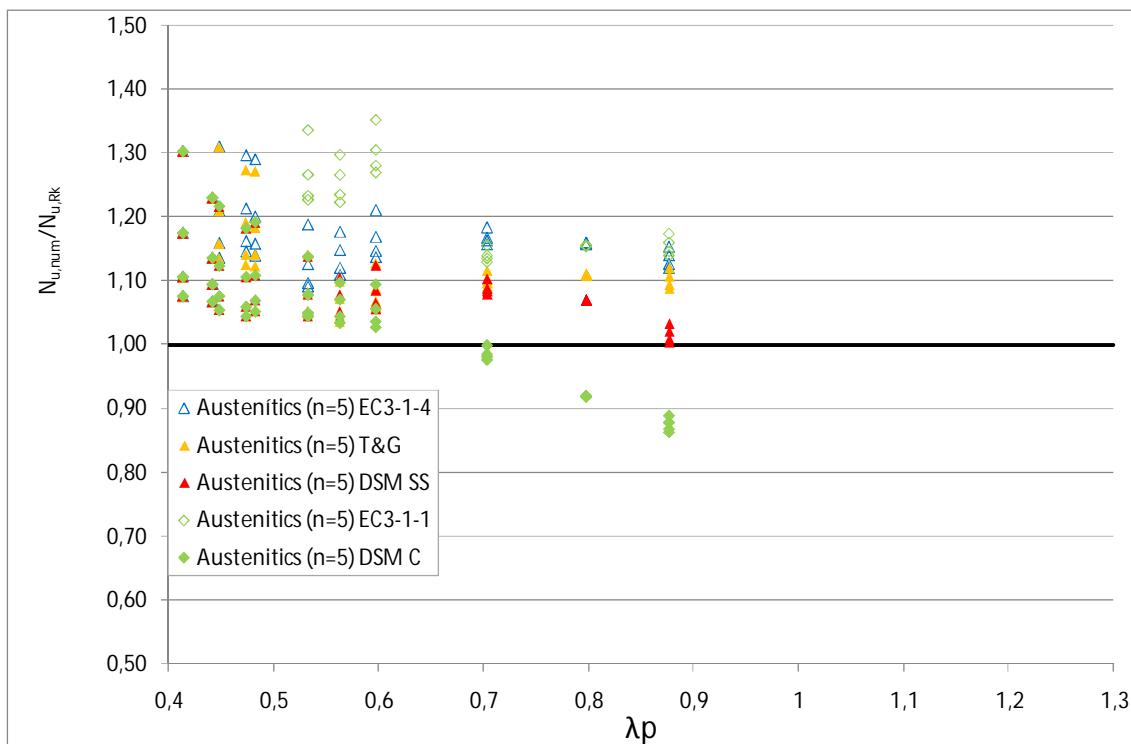


Figure 4.6 Comparison of analytical ultimate loads obtained according to the limits and reduction factors of EN1993-1-4, EN1993-1-5, G&T proposal and DSM for carbon steel and DSM for stainless steel. Austenitic stainless steel.

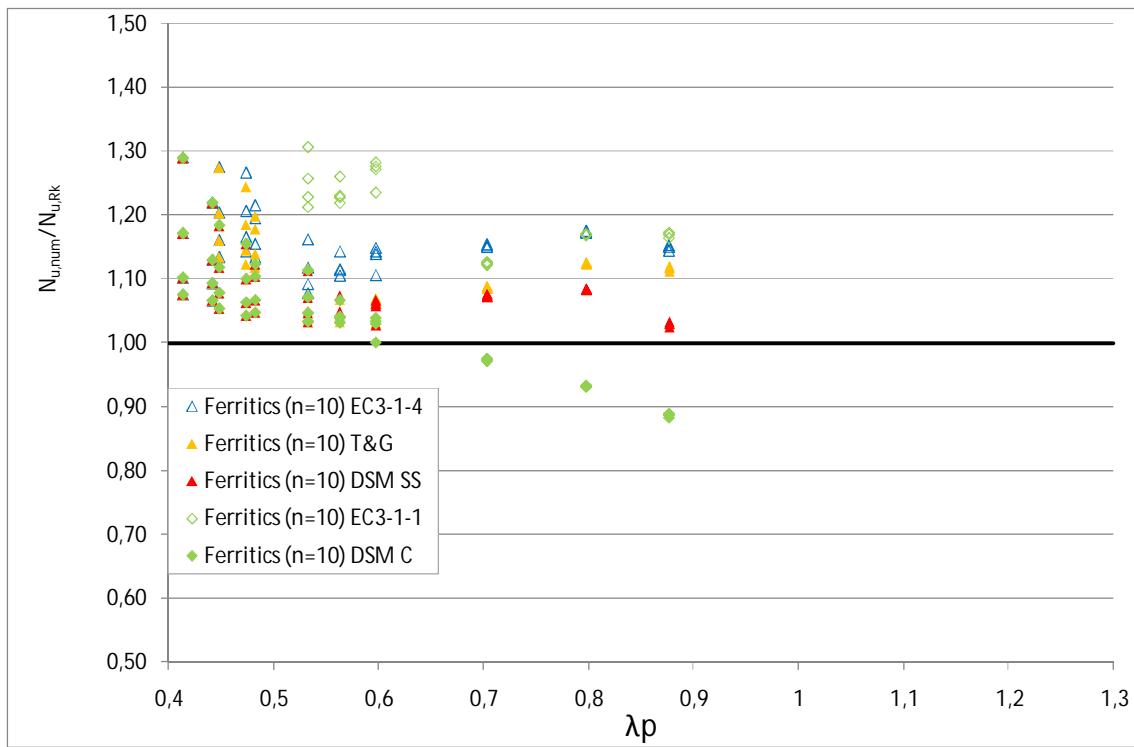


Figure 4.7 Comparison of analytical ultimate loads obtained according to the limits and reduction factors of EN1993-1-4, EN1993-1-5, G&T proposal and DSM for carbon steel and DSM for stainless steel. Ferritic stainless steel.

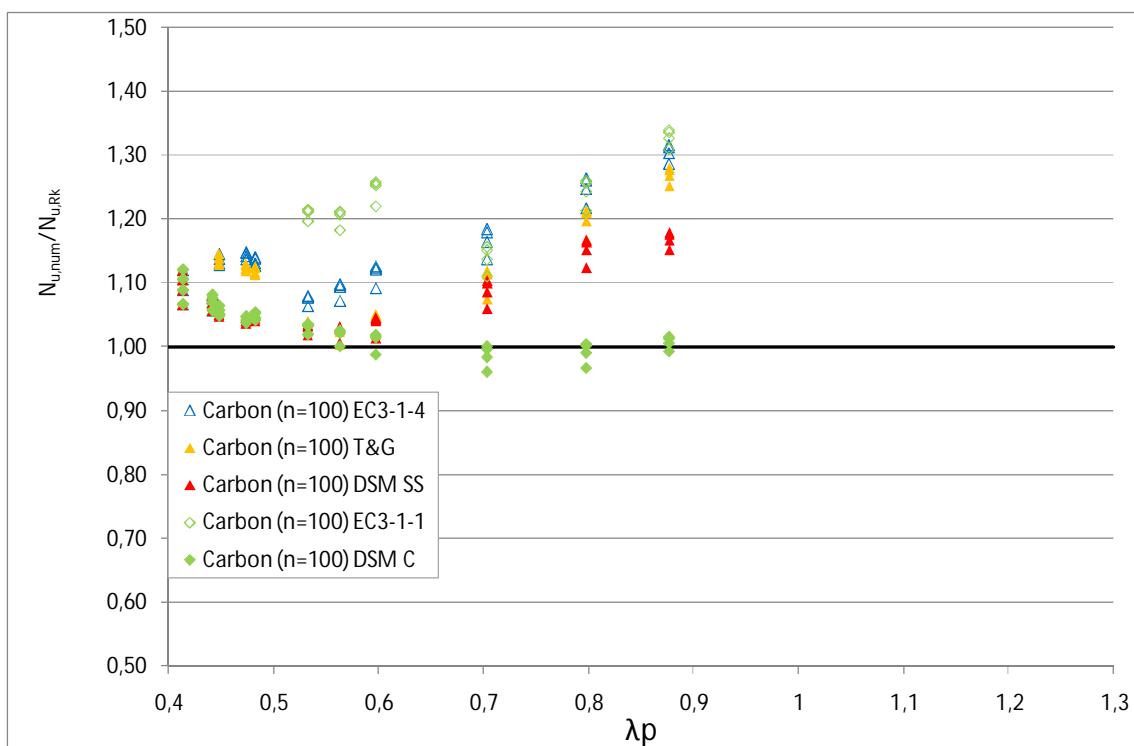


Figure 4.8 Comparison of analytical ultimate loads obtained according to the limits and reduction factors of EN1993-1-4, EN1993-1-5, G&T proposal and DSM for carbon steel and DSM for stainless steel. Carbon steel.

4.3 Channels

The results obtained in the parametric study for Channels are presented in figures 4.9 to 4.12 and similar conclusions to the SHS/RHS and I-sections can be drawn.

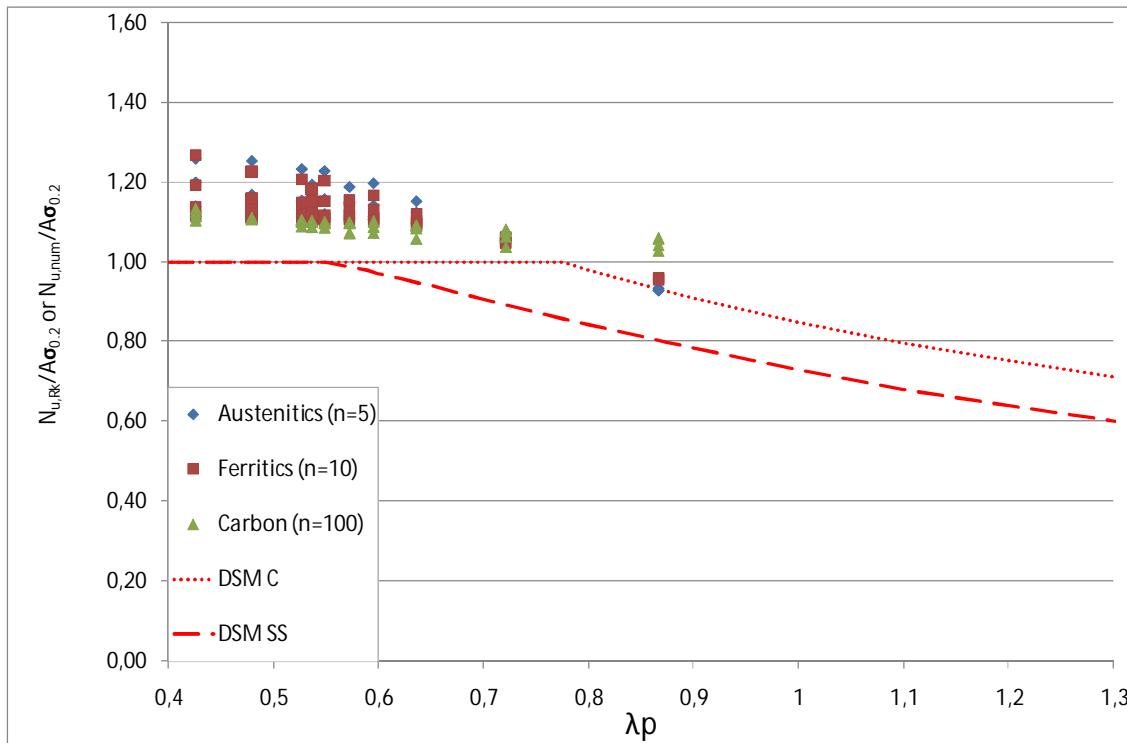


Figure 4.9 Assessment of the application of the DSM for fully compressed hollow sections (internal elements)

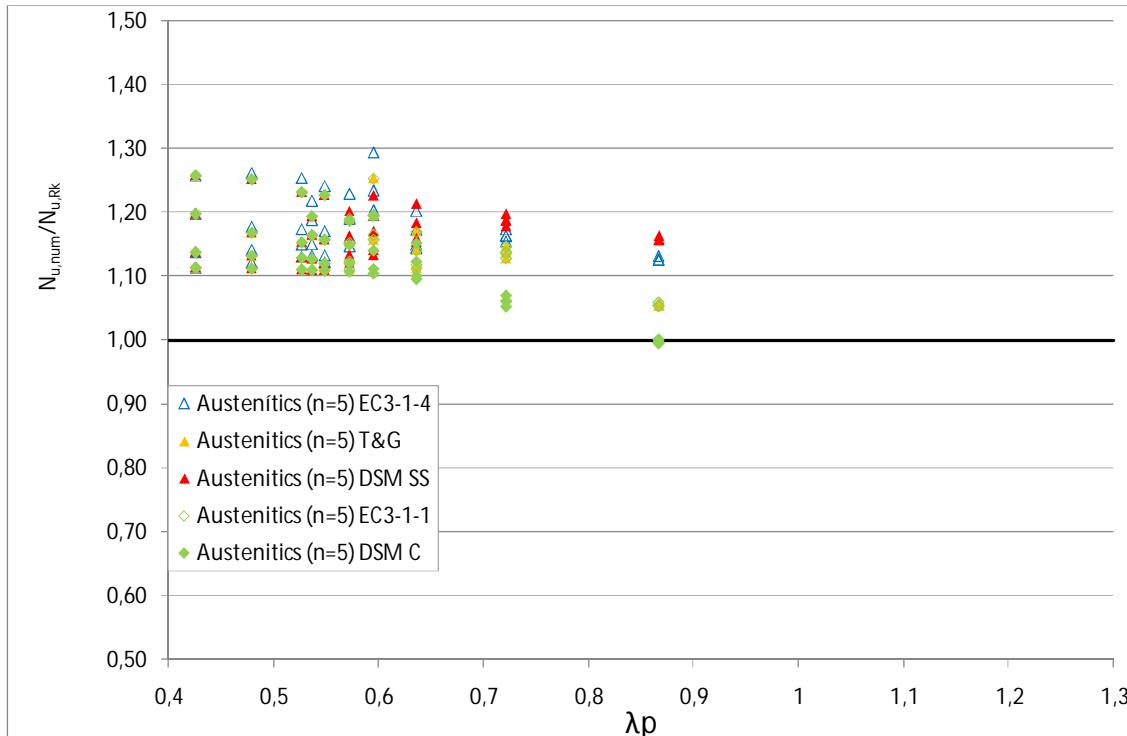


Figure 4.10 Comparison of analytical ultimate loads obtained according to the limits and reduction factors of EN1993-1-4, EN1993-1-5, G&T proposal and DSM for carbon steel and DSM for stainless steel. Austenitic stainless steel.

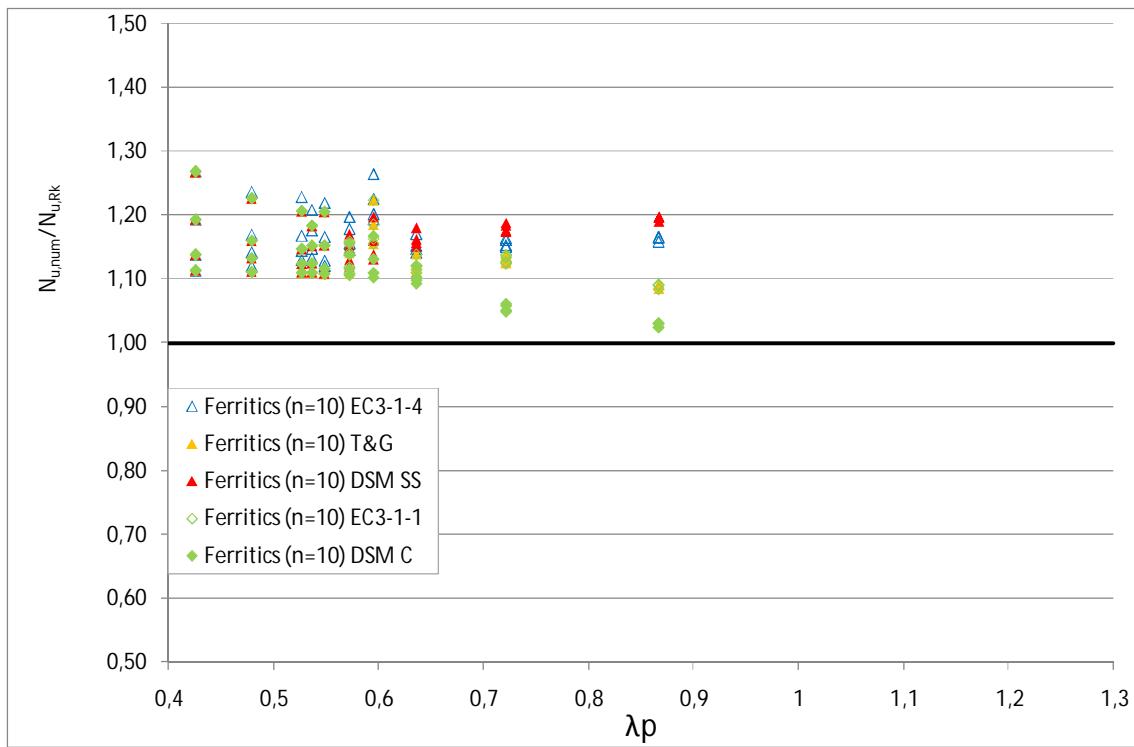


Figure 4.11 Comparison of analytical ultimate loads obtained according to the limits and reduction factors of EN1993-1-4, EN1993-1-5, G&T proposal and DSM for carbon steel and DSM for stainless steel. Ferritic stainless steel.

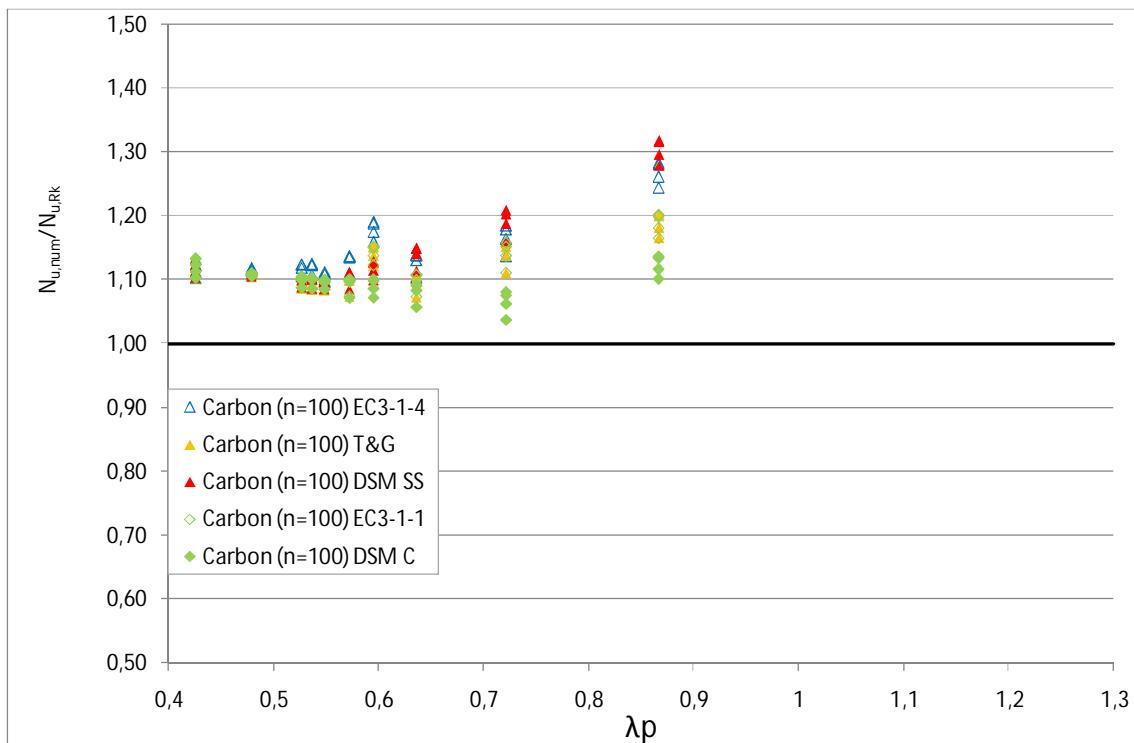


Figure 4.12 Comparison of analytical ultimate loads obtained according to the limits and reduction factors of EN1993-1-4, EN1993-1-5, G&T proposal and DSM for carbon steel and DSM for stainless steel. Carbon steel.

5. Conclusions

The applicability of the DSM to stainless steels has been studied in this task. The analysis has been performed in the same materials and cross-sections studied in previous tasks in order to compare the ultimate resistance obtained by a numerical analysis with the one obtained using different methods.

The first analysis related to the results obtained from the numerical analysis compared to the numerical ones allows concluding that:

- The DSM curve proposed for carbon steels fits very well the results for specimens with $n=100$ (carbon steels).
- For Austenitic stainless steels ($n=5$), the curve proposed in the DSM for stainless steels is quite conservative for not very slender elements, and the limit of $\lambda_p=0.55$ seems also conservative.
- Ferritic stainless steels behaves between carbon steels and austenitic stainless steels, so the curve for the DSM for stainless steels gives conservative results and could be improved for ferritics.

The results comparison using different methods to determine the ultimate resistance allows concluding that:

- Current EN1993-1-4 provides safe results for all the materials but is more conservative for high n values.
- G&T proposal provide a good evaluation for the ultimate capacity but there are some values in slender sections with a ratio $N_{u,num}/N_{u,Rk}$ below the unity. The maximum over prediction has been up to a 4%. The proposed curve by G&T is not a suitable reduction factor for the austenitics considered in this parametric study ($n=5$). However, it is important to mention that this proposal was calibrated considering experimental results in which the average n value material was about 6. (see WP2.4)
- The DSM for stainless steels provides good results for austenitic and ferritic stainless steels ($n=5$, $n=10$) but is quite conservative for carbon steel ($n=100$) where the DSM proposed for carbon steel is better.
- The two analyzed methods for carbon steel, EN 1993-1-5 and DSM for carbon steels, do not provide good results for austenitics and ferritics and will over predict their ultimate capacity, so cannot be used when designing stainless steel, but are good for carbon steels.

Finally, a wide analysis should be done with more slenderness sections, especially for Channels and I-sections and the interaction between local and global instabilities is also needed.

6. References

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Annex A. SHS/RHS sections results

Specimen	Cross-section properties						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	h (mm)	b (mm)	t (mm)	rm (mm)	ri (mm)	Ag (mm ²)	σu (MPa)	n	N _{u,num} (kN)	σ _{cr,num} (MPa)	σ _{crl} (Mpa)	λ _p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
S1M1	40	40	2	5	4	302.8	275	5	81.17	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S1M3	40	40	2	5	4	302.8	300	5	83.79	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S1M5	40	40	2	5	4	302.8	350	5	89.46	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S1M7	40	40	2	5	4	302.8	450	5	99.65	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S2M1	40	40	3	5.5	4	451.7	275	5	123.33	4307.67	4397.5	0.238	112.9	112.9	112.9	112.9	112.9
S2M3	40	40	3	5.5	4	451.7	300	5	128.12	4307.67	4397.5	0.238	112.9	112.9	112.9	112.9	112.9
S2M5	40	40	3	5.5	4	451.7	350	5	138.88	4307.67	4397.5	0.238	112.9	112.9	112.9	112.9	112.9
S2M7	40	40	3	5.5	4	451.7	450	5	161.35	4307.67	4397.5	0.238	112.9	112.9	112.9	112.9	112.9
S3M1	40	40	3	7.5	6	441.4	275	5	120.56	4656.33	4977.5	0.224	110.3	110.3	110.3	110.3	110.3
S3M3	40	40	3	7.5	6	441.4	300	5	125.24	4656.33	4977.5	0.224	110.3	110.3	110.3	110.3	110.3
S3M5	40	40	3	7.5	6	441.4	350	5	135.89	4656.33	4977.5	0.224	110.3	110.3	110.3	110.3	110.3
S3M7	40	40	3	7.5	6	441.4	450	5	158.37	4656.33	4977.5	0.224	110.3	110.3	110.3	110.3	110.3
S4M1	55	55	1.5	4.25	3.5	319.1	275	5	82.77	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4M3	55	55	1.5	4.25	3.5	319.1	300	5	82.88	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4M5	55	55	1.5	4.25	3.5	319.1	350	5	83.92	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4M7	55	55	1.5	4.25	3.5	319.1	450	5	85.69	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S5M1	65	65	1.5	4.25	3.5	379.1	275	5	85.9	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5M3	65	65	1.5	4.25	3.5	379.1	300	5	86.21	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5M5	65	65	1.5	4.25	3.5	379.1	350	5	87.36	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5M7	65	65	1.5	4.25	3.5	379.1	450	5	86.11	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4

S6M1	65	65	1.75	4.38	3.5	441.9	275	5	114.64	571.86	535	0.684	110.5	101.7	110.5	110.5	101.5
S6M3	65	65	1.75	4.38	3.5	441.9	300	5	114.64	571.86	535	0.684	110.5	101.7	110.5	110.5	101.5
S6M5	65	65	1.75	4.38	3.5	441.9	350	5	114.85	571.86	535	0.684	110.5	101.7	110.5	110.5	101.5
S6M7	65	65	1.75	4.38	3.5	441.9	450	5	115.58	571.86	535	0.684	110.5	101.7	110.5	110.5	101.5
S7M1	70	70	1.5	4.25	3.5	409.1	275	5	89.76	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S7M3	70	70	1.5	4.25	3.5	409.1	300	5	90.49	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S7M5	70	70	1.5	4.25	3.5	409.1	350	5	91.32	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S7M7	70	70	1.5	4.25	3.5	409.1	450	5	89.13	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S8M1	70	70	1.75	4.38	3.5	476.9	275	5	120.08	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8M3	70	70	1.75	4.38	3.5	476.9	300	5	120.19	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8M5	70	70	1.75	4.38	3.5	476.9	350	5	120.29	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8M7	70	70	1.75	4.38	3.5	476.9	450	5	115.9	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S9M1	90	90	1.75	4.38	3.5	616.9	275	5	121.34	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9M3	90	90	1.75	4.38	3.5	616.9	300	5	120.19	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9M5	90	90	1.75	4.38	3.5	616.9	350	5	120.08	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9M7	90	90	1.75	4.38	3.5	616.9	450	5	120.29	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S10M1	90	90	2	5	4	702.8	275	5	158.76	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10M3	90	90	2	5	4	702.8	300	5	158.13	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10M5	90	90	2	5	4	702.8	350	5	158.34	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10M7	90	90	2	5	4	702.8	450	5	161.07	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S11M1	100	100	2	5	4	782.8	275	5	161.81	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11M3	100	100	2	5	4	782.8	300	5	161.81	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11M5	100	100	2	5	4	782.8	350	5	161.81	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11M7	100	100	2	5	4	782.8	450	5	161.81	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S12M1	100	100	2.25	5.63	4.5	878.3	275	5	199.42	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12M3	100	100	2.25	5.63	4.5	878.3	300	5	199.31	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12M5	100	100	2.25	5.63	4.5	878.3	350	5	200.05	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3

S12M7	100	100	2.25	5.63	4.5	878.3	450	5	199.1	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S13M1	100	100	2.5	6.25	5	973.2	275	5	245.77	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13M3	100	100	2.5	6.25	5	973.2	300	5	241.44	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13M5	100	100	2.5	6.25	5	973.2	350	5	237.2	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13M7	100	100	2.5	6.25	5	973.2	450	5	245.14	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S14M1	100	100	3	5.5	4	1172	275	5	311.41	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14M3	100	100	3	5.5	4	1172	300	5	313.54	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14M5	100	100	3	5.5	4	1172	350	5	322.06	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14M7	100	100	3	5.5	4	1172	450	5	333.98	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S15M1	100	100	3	7.5	6	1161	275	5	309.6	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15M3	100	100	3	7.5	6	1161	300	5	311.83	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15M5	100	100	3	7.5	6	1161	350	5	320.25	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15M7	100	100	3	7.5	6	1161	450	5	332.92	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S16M1	110	110	2	5	4	862.8	275	5	161.18	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16M3	110	110	2	5	4	862.8	300	5	160.86	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16M5	110	110	2	5	4	862.8	350	5	160.34	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16M7	110	110	2	5	4	862.8	450	5	160.02	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S17M1	120	120	2	5	4	942.8	275	5	160.91	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17M3	120	120	2	5	4	942.8	300	5	160.38	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17M5	120	120	2	5	4	942.8	350	5	160.91	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17M7	120	120	2	5	4	942.8	450	5	160.27	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S18M1	130	130	2	5	4	1023	275	5	160.71	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18M3	130	130	2	5	4	1023	300	5	160.61	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18M5	130	130	2	5	4	1023	350	5	160.18	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18M7	130	130	2	5	4	1023	450	5	160.29	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S19M1	140	140	2	5	4	1103	275	5	161.87	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19M3	140	140	2	5	4	1103	300	5	161.87	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4

S19M5	140	140	2	5	4	1103	350	5	161.87	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19M7	140	140	2	5	4	1103	450	5	161.54	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
R1M1	80	60	1.75	4.38	3.5	476.9	275	5	116	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1M3	80	60	1.75	4.38	3.5	476.9	300	5	116.32	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1M5	80	60	1.75	4.38	3.5	476.9	350	5	116.52	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1M7	80	60	1.75	4.38	3.5	476.9	450	5	116.63	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R2M1	80	60	2	5	4	542.8	275	5	140.49	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2M3	80	60	2	5	4	542.8	300	5	141.75	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2M5	80	60	2	5	4	542.8	350	5	143.12	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2M7	80	60	2	5	4	542.8	450	5	147	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R3M1	80	60	2.25	5.63	4.5	608.3	275	5	161.68	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3M3	80	60	2.25	5.63	4.5	608.3	300	5	163.05	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3M5	80	60	2.25	5.63	4.5	608.3	350	5	167.69	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3M7	80	60	2.25	5.63	4.5	608.3	450	5	172.86	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R4M1	80	60	3	5.5	4	811.7	275	5	219.07	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4M3	80	60	3	5.5	4	811.7	300	5	224.5	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4M5	80	60	3	5.5	4	811.7	350	5	234.19	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4M7	80	60	3	5.5	4	811.7	450	5	253.36	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R5M1	80	60	3	7.5	6	801.4	275	5	216.62	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5M3	80	60	3	7.5	6	801.4	300	5	221.63	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5M5	80	60	3	7.5	6	801.4	350	5	233.02	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5M7	80	60	3	7.5	6	801.4	450	5	253.04	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
S1M2	40	40	2	5	4	302.8	275	10	81.06	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S1M4	40	40	2	5	4	302.8	300	10	83.69	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S1M6	40	40	2	5	4	302.8	350	10	88.73	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S1M8	40	40	2	5	4	302.8	450	10	98.81	2015.87	1960	0.357	75.7	75.7	75.7	75.7	75.7
S2M2	40	40	3	5.5	4	451.7	275	10	123.22	4307.67	4187.5	0.244	112.9	112.9	112.9	112.9	112.9

S2M4	40	40	3	5.5	4	451.7	300	10	128.01	4307.67	4187.5	0.244	112.9	112.9	112.9	112.9	112.9
S2M6	40	40	3	5.5	4	451.7	350	10	138.66	4307.67	4187.5	0.244	112.9	112.9	112.9	112.9	112.9
S2M8	40	40	3	5.5	4	451.7	450	10	161.03	4307.67	4187.5	0.244	112.9	112.9	112.9	112.9	112.9
S3M2	40	40	3	7.5	6	441.4	275	10	120.56	4656.33	4750	0.229	110.3	110.3	110.3	110.3	110.3
S3M4	40	40	3	7.5	6	441.4	300	10	125.14	4656.33	4750	0.229	110.3	110.3	110.3	110.3	110.3
S3M6	40	40	3	7.5	6	441.4	350	10	135.57	4656.33	4750	0.229	110.3	110.3	110.3	110.3	110.3
S3M8	40	40	3	7.5	6	441.4	450	10	157.51	4656.33	4750	0.229	110.3	110.3	110.3	110.3	110.3
S4M2	55	55	1.5	4.25	3.5	319.1	275	10	82.15	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4M4	55	55	1.5	4.25	3.5	319.1	300	10	81.52	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4M6	55	55	1.5	4.25	3.5	319.1	350	10	82.04	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4M8	55	55	1.5	4.25	3.5	319.1	450	10	82.04	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S5M2	65	65	1.5	4.25	3.5	379.1	275	10	91.22	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5M4	65	65	1.5	4.25	3.5	379.1	300	10	91.22	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5M6	65	65	1.5	4.25	3.5	379.1	350	10	90.49	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5M8	65	65	1.5	4.25	3.5	379.1	450	10	91.01	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S6M2	65	65	1.75	4.38	3.5	441.9	275	10	113.91	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S6M4	65	65	1.75	4.38	3.5	441.9	300	10	114.22	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S6M6	65	65	1.75	4.38	3.5	441.9	350	10	114.01	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S6M8	65	65	1.75	4.38	3.5	441.9	450	10	114.85	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S7M2	70	70	1.5	4.25	3.5	409.1	275	10	94.03	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S7M4	70	70	1.5	4.25	3.5	409.1	300	10	93.93	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S7M6	70	70	1.5	4.25	3.5	409.1	350	10	93.93	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S7M8	70	70	1.5	4.25	3.5	409.1	450	10	93.41	363.96	340	0.857	94.0	82.0	88.4	96.1	82.7
S8M2	70	70	1.75	4.38	3.5	476.9	275	10	119.03	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8M4	70	70	1.75	4.38	3.5	476.9	300	10	117.68	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8M6	70	70	1.75	4.38	3.5	476.9	350	10	118.2	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8M8	70	70	1.75	4.38	3.5	476.9	450	10	117.57	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4

S9M2	90	90	1.75	4.38	3.5	616.9	275	10	131.69	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9M4	90	90	1.75	4.38	3.5	616.9	300	10	131.69	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9M6	90	90	1.75	4.38	3.5	616.9	350	10	131.48	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9M8	90	90	1.75	4.38	3.5	616.9	450	10	131.69	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S10M2	90	90	2	5	4	702.8	275	10	164.01	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10M4	90	90	2	5	4	702.8	300	10	164.12	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10M6	90	90	2	5	4	702.8	350	10	164.22	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10M8	90	90	2	5	4	702.8	450	10	161.81	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S11M2	100	100	2	5	4	782.8	275	10	167.79	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11M4	100	100	2	5	4	782.8	300	10	167.9	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11M6	100	100	2	5	4	782.8	350	10	167.79	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11M8	100	100	2	5	4	782.8	450	10	169.05	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S12M2	100	100	2.25	5.63	4.5	878.3	275	10	208.38	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12M4	100	100	2.25	5.63	4.5	878.3	300	10	208.27	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12M6	100	100	2.25	5.63	4.5	878.3	350	10	208.27	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12M8	100	100	2.25	5.63	4.5	878.3	450	10	208.27	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S13M2	100	100	2.5	6.25	5	973.2	275	10	240.8	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13M4	100	100	2.5	6.25	5	973.2	300	10	240.7	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13M6	100	100	2.5	6.25	5	973.2	350	10	241.65	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13M8	100	100	2.5	6.25	5	973.2	450	10	247.04	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S14M2	100	100	3	5.5	4	1172	275	10	308.74	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14M4	100	100	3	5.5	4	1172	300	10	310.77	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14M6	100	100	3	5.5	4	1172	350	10	317.8	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14M8	100	100	3	5.5	4	1172	450	10	325.89	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S15M2	100	100	3	7.5	6	1161	275	10	307.68	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15M4	100	100	3	7.5	6	1161	300	10	309.6	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15M6	100	100	3	7.5	6	1161	350	10	316.41	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3

S15M8	100	100	3	7.5	6	1161	450	10	322.48	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S16M2	110	110	2	5	4	862.8	275	10	173.15	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16M4	110	110	2	5	4	862.8	300	10	173.78	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16M6	110	110	2	5	4	862.8	350	10	173.25	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16M8	110	110	2	5	4	862.8	450	10	172.52	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S17M2	120	120	2	5	4	942.8	275	10	176.6	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17M4	120	120	2	5	4	942.8	300	10	176.6	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17M6	120	120	2	5	4	942.8	350	10	176.28	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17M8	120	120	2	5	4	942.8	450	10	175.64	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S18M2	130	130	2	5	4	1023	275	10	176.76	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18M4	130	130	2	5	4	1023	300	10	176.66	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18M6	130	130	2	5	4	1023	350	10	176.66	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18M8	130	130	2	5	4	1023	450	10	175.8	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S19M2	140	140	2	5	4	1103	275	10	178.65	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19M4	140	140	2	5	4	1103	300	10	178.54	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19M6	140	140	2	5	4	1103	350	10	178.32	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19M8	140	140	2	5	4	1103	450	10	177.56	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
R1M2	80	60	1.75	4.38	3.5	476.9	275	10	115.58	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1M4	80	60	1.75	4.38	3.5	476.9	300	10	115.69	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1M6	80	60	1.75	4.38	3.5	476.9	350	10	115.69	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1M8	80	60	1.75	4.38	3.5	476.9	450	10	115.79	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R2M2	80	60	2	5	4	542.8	275	10	140.18	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2M4	80	60	2	5	4	542.8	300	10	138.81	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2M6	80	60	2	5	4	542.8	350	10	138.39	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2M8	80	60	2	5	4	542.8	450	10	142.91	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R3M2	80	60	2.25	5.63	4.5	608.3	275	10	160.74	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3M4	80	60	2.25	5.63	4.5	608.3	300	10	160.74	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5

R3M6	80	60	2.25	5.63	4.5	608.3	350	10	165.79	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3M8	80	60	2.25	5.63	4.5	608.3	450	10	168.53	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R4M2	80	60	3	5.5	4	811.7	275	10	219.28	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4M4	80	60	3	5.5	4	811.7	300	10	224.18	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4M6	80	60	3	5.5	4	811.7	350	10	231.32	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4M8	80	60	3	5.5	4	811.7	450	10	252.72	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R5M2	80	60	3	7.5	6	801.4	275	10	216.41	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5M4	80	60	3	7.5	6	801.4	300	10	221.2	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5M6	80	60	3	7.5	6	801.4	350	10	231	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5M8	80	60	3	7.5	6	801.4	450	10	250.49	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
S1C1	40	40	2	5	4	302.8	275	100	80.85	2015.87	1955	0.358	75.7	75.7	75.7	75.7	75.7
S1C2	40	40	2	5	4	302.8	300	100	82.53	2015.87	1955	0.358	75.7	75.7	75.7	75.7	75.7
S1C3	40	40	2	5	4	302.8	350	100	84.21	2015.87	1955	0.358	75.7	75.7	75.7	75.7	75.7
S1C4	40	40	2	5	4	302.8	450	100	86.31	2015.87	1955	0.358	75.7	75.7	75.7	75.7	75.7
S2C1	40	40	3	5.5	4	451.7	275	100	123.01	4307.67	4195	0.244	112.9	112.9	112.9	112.9	112.9
S2C2	40	40	3	5.5	4	451.7	300	100	126.52	4307.67	4195	0.244	112.9	112.9	112.9	112.9	112.9
S2C3	40	40	3	5.5	4	451.7	350	100	133.87	4307.67	4195	0.244	112.9	112.9	112.9	112.9	112.9
S2C4	40	40	3	5.5	4	451.7	450	100	143.03	4307.67	4195	0.244	112.9	112.9	112.9	112.9	112.9
S3C1	40	40	3	7.5	6	441.4	275	100	120.24	4656.33	4725	0.230	110.3	110.3	110.3	110.3	110.3
S3C2	40	40	3	7.5	6	441.4	300	100	123.97	4656.33	4725	0.230	110.3	110.3	110.3	110.3	110.3
S3C3	40	40	3	7.5	6	441.4	350	100	131.31	4656.33	4725	0.230	110.3	110.3	110.3	110.3	110.3
S3C4	40	40	3	7.5	6	441.4	450	100	142.28	4656.33	4725	0.230	110.3	110.3	110.3	110.3	110.3
S4C1	55	55	1.5	4.25	3.5	319.1	275	100	82.57	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4C2	55	55	1.5	4.25	3.5	319.1	300	100	82.36	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4C3	55	55	1.5	4.25	3.5	319.1	350	100	81.73	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S4C4	55	55	1.5	4.25	3.5	319.1	450	100	79.65	594.52	562.5	0.667	79.8	74.9	79.8	79.8	74.2
S5C1	65	65	1.5	4.25	3.5	379.1	275	100	96.54	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4

S5C2	65	65	1.5	4.25	3.5	379.1	300	100	96.33	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5C3	65	65	1.5	4.25	3.5	379.1	350	100	94.97	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S5C4	65	65	1.5	4.25	3.5	379.1	450	100	92.89	423.04	397.5	0.793	94.8	80.0	86.8	93.5	80.4
S6C1	65	65	1.75	4.38	3.5	441.9	275	100	114.43	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S6C2	65	65	1.75	4.38	3.5	441.9	300	100	114.33	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S6C3	65	65	1.75	4.38	3.5	441.9	350	100	113.39	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S6C4	65	65	1.75	4.38	3.5	441.9	450	100	110.25	571.86	537.5	0.682	110.5	101.7	110.5	110.5	101.5
S7C1	70	70	1.5	4.25	3.5	409.1	275	100	102.79	363.96	342.5	0.854	94.0	82.0	88.4	96.3	82.7
S7C2	70	70	1.5	4.25	3.5	409.1	300	100	102.79	363.96	342.5	0.854	94.0	82.0	88.4	96.3	82.7
S7C3	70	70	1.5	4.25	3.5	409.1	350	100	101.85	363.96	342.5	0.854	94.0	82.0	88.4	96.3	82.7
S7C4	70	70	1.5	4.25	3.5	409.1	450	100	99.66	363.96	342.5	0.854	94.0	82.0	88.4	96.3	82.7
S8C1	70	70	1.75	4.38	3.5	476.9	275	100	122.8	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8C2	70	70	1.75	4.38	3.5	476.9	300	100	122.28	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8C3	70	70	1.75	4.38	3.5	476.9	350	100	120.81	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S8C4	70	70	1.75	4.38	3.5	476.9	450	100	117.99	492.4	460	0.737	119.2	104.8	119.2	119.2	105.4
S9C1	90	90	1.75	4.38	3.5	616.9	275	100	150.41	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9C2	90	90	1.75	4.38	3.5	616.9	300	100	148.95	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9C3	90	90	1.75	4.38	3.5	616.9	350	100	142.67	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S9C4	90	90	1.75	4.38	3.5	616.9	450	100	147.28	296.87	275	0.953	132.3	113.8	121.5	135.2	116.3
S10C1	90	90	2	5	4	702.8	275	100	178.71	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10C2	90	90	2	5	4	702.8	300	100	178.92	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10C3	90	90	2	5	4	702.8	350	100	176.72	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S10C4	90	90	2	5	4	702.8	450	100	172.94	388.37	362.5	0.830	163.5	142.8	154.2	168.4	144.9
S11C1	100	100	2	5	4	782.8	275	100	194.15	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11C2	100	100	2	5	4	782.8	300	100	193.62	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11C3	100	100	2	5	4	782.8	350	100	192.78	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7
S11C4	100	100	2	5	4	782.8	450	100	189.63	314.21	292.5	0.925	170.9	147.4	157.8	175.1	150.7

S12C1	100	100	2.25	5.63	4.5	878.3	275	100	225.24	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12C2	100	100	2.25	5.63	4.5	878.3	300	100	224.92	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12C3	100	100	2.25	5.63	4.5	878.3	350	100	221.87	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S12C4	100	100	2.25	5.63	4.5	878.3	450	100	217.23	398.19	370	0.822	219.6	179.9	194.6	211.8	182.3
S13C1	100	100	2.5	6.25	5	973.2	275	100	252.23	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13C2	100	100	2.5	6.25	5	973.2	300	100	250.01	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13C3	100	100	2.5	6.25	5	973.2	350	100	247.78	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S13C4	100	100	2.5	6.25	5	973.2	450	100	243.45	492.37	460	0.737	243.3	213.9	243.3	243.3	215.0
S14C1	100	100	3	5.5	4	1172	275	100	311.3	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14C2	100	100	3	5.5	4	1172	300	100	311.51	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14C3	100	100	3	5.5	4	1172	350	100	309.49	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S14C4	100	100	3	5.5	4	1172	450	100	302.25	699.57	650	0.620	292.9	280.5	292.9	292.9	281.1
S15C1	100	100	3	7.5	6	1161	275	100	308.96	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15C2	100	100	3	7.5	6	1161	300	100	308.64	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15C3	100	100	3	7.5	6	1161	350	100	308.1	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S15C4	100	100	3	7.5	6	1161	450	100	300.44	711.65	670	0.611	290.3	290.3	290.3	290.3	280.3
S16C1	110	110	2	5	4	862.8	275	100	201.81	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16C2	110	110	2	5	4	862.8	300	100	191	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16C3	110	110	2	5	4	862.8	350	100	200.45	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S16C4	110	110	2	5	4	862.8	450	100	198.35	259.47	240	1.021	177.0	151.3	160.7	180.9	155.2
S17C1	120	120	2	5	4	942.8	275	100	201.29	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17C2	120	120	2	5	4	942.8	300	100	200.98	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17C2	120	120	2	5	4	942.8	350	100	199.92	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S17C4	120	120	2	5	4	942.8	450	100	199.28	217.9	202.5	1.111	182.1	154.5	163.1	186.8	159.5
S18C1	130	130	2	5	4	1023	275	100	198.7	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18C2	130	130	2	5	4	1023	300	100	198.38	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S18C3	130	130	2	5	4	1023	350	100	197.2	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0

S18C4	130	130	2	5	4	1023	450	100	195.6	185.59	172.5	1.204	186.5	157.2	165.2	191.9	163.0
S19C1	140	140	2	5	4	1103	275	100	198.27	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19C2	140	140	2	5	4	1103	300	100	198.16	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19C3	140	140	2	5	4	1103	350	100	197.73	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
S19C4	140	140	2	5	4	1103	450	100	196.85	159.98	147.5	1.302	190.2	159.5	166.9	196.1	165.4
R1C1	80	60	1.75	4.38	3.5	476.9	275	100	122.07	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1C2	80	60	1.75	4.38	3.5	476.9	300	100	121.65	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1C3	80	60	1.75	4.38	3.5	476.9	350	100	120.08	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R1C4	80	60	1.75	4.38	3.5	476.9	450	100	117.99	441.83	422.5	0.769	113.9	104.0	110.1	119.2	102.9
R2C1	80	60	2	5	4	542.8	275	100	140.18	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2C2	80	60	2	5	4	542.8	300	100	140.91	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2C3	80	60	2	5	4	542.8	350	100	139.55	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R2C4	80	60	2	5	4	542.8	450	100	135.98	578.7	555	0.671	135.7	126.3	135.7	135.7	125.8
R3C1	80	60	2.25	5.63	4.5	608.3	275	100	160.1	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3C2	80	60	2.25	5.63	4.5	608.3	300	100	160.21	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3C3	80	60	2.25	5.63	4.5	608.3	350	100	160.31	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R3C4	80	60	2.25	5.63	4.5	608.3	450	100	157.05	734.77	710	0.593	152.1	147.3	152.1	152.1	148.5
R4C1	80	60	3	5.5	4	811.7	275	100	218.33	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4C2	80	60	3	5.5	4	811.7	300	100	220.35	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4C3	80	60	3	5.5	4	811.7	350	100	221.52	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R4C4	80	60	3	5.5	4	811.7	450	100	222.16	1281.3	1230	0.451	202.9	202.9	202.9	202.9	202.9
R5C1	80	60	3	7.5	6	801.4	275	100	215.98	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5C2	80	60	3	7.5	6	801.4	300	100	218.11	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5C3	80	60	3	7.5	6	801.4	350	100	218.86	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3
R5C4	80	60	3	7.5	6	801.4	450	100	219.18	1320.22	1295	0.439	200.3	200.3	200.3	200.3	200.3

Annex B . Channel sections results

Specimen	Cross-section properties (mm)						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	H (mm)	B (mm)	tw (mm)	tf (mm)	rm (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
C1M1	40	30	2	2	5	183.4	275	5	50.71	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1M3	40	30	2	2	5	183.4	300	5	51.04	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1M5	40	30	2	2	5	183.4	350	5	52.36	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1M7	40	30	2	2	5	183.4	450	5	54.89	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C2M1	40	30	3	3	7.5	262.7	275	5	73.81	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2M3	40	30	3	3	7.5	262.7	300	5	75.79	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2M5	40	30	3	3	7.5	262.7	350	5	79.75	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2M7	40	30	3	3	7.5	262.7	450	5	88.22	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C3M1	60	30	3	3	7.5	322.7	275	5	89.87	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3M3	60	30	3	3	7.5	322.7	300	5	91.85	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3M5	60	30	3	3	7.5	322.7	350	5	96.69	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3M7	60	30	3	3	7.5	322.7	450	5	101.53	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C4M1	60	35	3	3	7.5	352.7	275	5	98.12	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4M3	60	35	3	3	7.5	352.7	300	5	99.88	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4M5	60	35	3	3	7.5	352.7	350	5	103.07	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4M7	60	35	3	3	7.5	352.7	450	5	110.44	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C5M1	80	40	3.25	3.25	8.125	476.2	275	5	132.33	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5M3	80	40	3.25	3.25	8.125	476.2	300	5	134.53	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5M5	80	40	3.25	3.25	8.125	476.2	350	5	137.39	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5M7	80	40	3.25	3.25	8.125	476.2	450	5	146.74	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1

Specimen	Cross-section properties (mm)						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	H (mm)	B (mm)	tw (mm)	tf (mm)	rm (mm)	Ag (mm ²)	σ _u (MPa)	n	N _{u,num} (kN)	σ _{cr,num} (MPa)	σ _{crl} (Mpa)	λ _p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
C6M1	80	40	3	3	7.5	442.7	275	5	122.65	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6M3	80	40	3	3	7.5	442.7	300	5	124.08	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6M5	80	40	3	3	7.5	442.7	350	5	127.27	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6M7	80	40	3	3	7.5	442.7	450	5	131.45	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C7M1	100	50	3	3	7.5	562.7	275	5	149.38	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7M3	100	50	3	3	7.5	562.7	300	5	148.17	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7M5	100	50	3	3	7.5	562.7	350	5	149.27	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7M7	100	50	3	3	7.5	562.7	450	5	150.59	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C8M1	100	50	4	4	10	733.7	275	5	203.61	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8M3	100	50	4	4	10	733.7	300	5	206.8	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8M5	100	50	4	4	10	733.7	350	5	213.62	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8M7	100	50	4	4	10	733.7	450	5	219.01	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C9M1	120	60	3	3	7.5	682.7	275	5	158.62	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9M3	120	60	3	3	7.5	682.7	300	5	158.62	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9M5	120	60	3	3	7.5	682.7	350	5	159.39	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9M7	120	60	3	3	7.5	682.7	450	5	158.51	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C10M1	140	60	5	5	12.5	1196	275	5	331.87	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10M3	140	60	5	5	12.5	1196	300	5	335.06	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10M5	140	60	5	5	12.5	1196	350	5	346.28	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10M7	140	60	5	5	12.5	1196	450	5	367.18	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C11M1	160	70	5	5	12.5	1396	275	5	384.34	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C11M3	160	70	5	5	12.5	1396	300	5	382.58	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5

Specimen	Cross-section properties (mm)						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	H (mm)	B (mm)	tw (mm)	tf (mm)	rm (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
C11M5	160	70	5	5	12.5	1396	350	5	392.26	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C11M7	160	70	5	5	12.5	1396	450	5	402.16	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C1M2	40	30	2	2	5	183.4	275	10	50.6	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1M4	40	30	2	2	5	183.4	300	10	50.93	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1M6	40	30	2	2	5	183.4	350	10	51.92	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1M8	40	30	2	2	5	183.4	450	10	53.57	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C2M2	40	30	3	3	7.5	262.7	275	10	73.7	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2M4	40	30	3	3	7.5	262.7	300	10	75.68	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2M6	40	30	3	3	7.5	262.7	350	10	79.2	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2M8	40	30	3	3	7.5	262.7	450	10	87.34	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C3M2	60	30	3	3	7.5	322.7	275	10	89.87	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3M4	60	30	3	3	7.5	322.7	300	10	91.85	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3M6	60	30	3	3	7.5	322.7	350	10	96.25	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3M8	60	30	3	3	7.5	322.7	450	10	102.3	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C4M2	60	35	3	3	7.5	352.7	275	10	98.01	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4M4	60	35	3	3	7.5	352.7	300	10	99.88	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4M6	60	35	3	3	7.5	352.7	350	10	102.3	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4M8	60	35	3	3	7.5	352.7	450	10	108.13	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C5M2	80	40	3.25	3.25	8.125	476.2	275	10	132.22	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5M4	80	40	3.25	3.25	8.125	476.2	300	10	133.87	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5M6	80	40	3.25	3.25	8.125	476.2	350	10	136.62	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5M8	80	40	3.25	3.25	8.125	476.2	450	10	143.66	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1

Specimen	Cross-section properties (mm)						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	H (mm)	B (mm)	tw (mm)	tf (mm)	rm (mm)	Ag (mm ²)	σ _u (MPa)	n	N _{u,num} (kN)	σ _{cr,num} (MPa)	σ _{crl} (Mpa)	λ _p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
C6M2	80	40	3	3	7.5	442.7	275	10	122.43	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6M4	80	40	3	3	7.5	442.7	300	10	123.53	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6M6	80	40	3	3	7.5	442.7	350	10	125.95	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6M8	80	40	3	3	7.5	442.7	450	10	127.93	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C7M2	100	50	3	3	7.5	562.7	275	10	147.62	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7M4	100	50	3	3	7.5	562.7	300	10	148.94	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7M6	100	50	3	3	7.5	562.7	350	10	149.38	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7M8	100	50	3	3	7.5	562.7	450	10	147.95	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C8M2	100	50	4	4	10	733.7	275	10	203.61	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8M4	100	50	4	4	10	733.7	300	10	206.25	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8M6	100	50	4	4	10	733.7	350	10	211.31	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8M8	100	50	4	4	10	733.7	450	10	217.03	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C9M2	120	60	3	3	7.5	682.7	275	10	164.12	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9M4	120	60	3	3	7.5	682.7	300	10	164.12	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9M6	120	60	3	3	7.5	682.7	350	10	164.01	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9M8	120	60	3	3	7.5	682.7	450	10	163.13	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C10M2	140	60	5	5	12.5	1196	275	10	331.43	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10M4	140	60	5	5	12.5	1196	300	10	333.85	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10M6	140	60	5	5	12.5	1196	350	10	344.74	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10M8	140	60	5	5	12.5	1196	450	10	360.36	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C11M2	160	70	5	5	12.5	1396	275	10	383.46	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C11M4	160	70	5	5	12.5	1396	300	10	381.59	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5

Specimen	Cross-section properties (mm)						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	H (mm)	B (mm)	tw (mm)	tf (mm)	rm (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
C11M6	160	70	5	5	12.5	1396	350	10	385.22	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C11M8	160	70	5	5	12.5	1396	450	10	391.27	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C1C1	40	30	2	2	5	183.4	275	100	49.83	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1C2	40	30	2	2	5	183.4	300	100	50.38	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1C3	40	30	2	2	5	183.4	350	100	50.49	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C1C4	40	30	2	2	5	183.4	450	100	49.17	945.44	705	0.595	43.8	42.4	43.8	45.9	44.7
C2C1	40	30	3	3	7.5	262.7	275	100	73.48	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2C2	40	30	3	3	7.5	262.7	300	100	74.47	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2C3	40	30	3	3	7.5	262.7	350	100	75.35	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C2C4	40	30	3	3	7.5	262.7	450	100	76.12	2243.1	1640	0.390	65.7	65.7	65.7	65.7	65.7
C3C1	60	30	3	3	7.5	322.7	275	100	88.99	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3C2	60	30	3	3	7.5	322.7	300	100	89.76	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3C3	60	30	3	3	7.5	322.7	350	100	90.64	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C3C4	60	30	3	3	7.5	322.7	450	100	91.41	1637.75	1378	0.426	80.7	80.7	80.7	80.7	80.7
C4C1	60	35	3	3	7.5	352.7	275	100	97.46	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4C2	60	35	3	3	7.5	352.7	300	100	97.9	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4C3	60	35	3	3	7.5	352.7	350	100	97.79	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C4C4	60	35	3	3	7.5	352.7	450	100	97.57	1331.13	1088	0.479	88.2	87.5	88.2	88.2	88.2
C5C1	80	40	3.25	3.25	8.125	476.2	275	100	130.9	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5C2	80	40	3.25	3.25	8.125	476.2	300	100	131.45	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5C3	80	40	3.25	3.25	8.125	476.2	350	100	131.56	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1
C5C4	80	40	3.25	3.25	8.125	476.2	450	100	129.47	1054.7	900	0.527	119.1	117.0	119.1	119.1	119.1

Specimen	Cross-section properties (mm)						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	H (mm)	B (mm)	tw (mm)	tf (mm)	rm (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
C6C1	80	40	3	3	7.5	442.7	275	100	121.33	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6C2	80	40	3	3	7.5	442.7	300	100	121.55	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6C3	80	40	3	3	7.5	442.7	350	100	121.44	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C6C4	80	40	3	3	7.5	442.7	450	100	118.58	890.37	762.5	0.573	110.4	106.9	110.4	110.7	109.4
C7C1	100	50	3	3	7.5	562.7	275	100	152.02	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7C2	100	50	3	3	7.5	562.7	300	100	151.25	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7C3	100	50	3	3	7.5	562.7	350	100	149.38	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C7C4	100	50	3	3	7.5	562.7	450	100	145.86	559.31	480	0.722	131.3	128.3	131.3	140.7	125.8
C8C1	100	50	4	4	10	733.7	275	100	201.74	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8C2	100	50	4	4	10	733.7	300	100	202.18	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8C3	100	50	4	4	10	733.7	350	100	201.96	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C8C4	100	50	4	4	10	733.7	450	100	199.1	1020.76	867.5	0.537	183.4	179.7	183.4	183.4	183.4
C9C1	120	60	3	3	7.5	682.7	275	100	180.73	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9C2	120	60	3	3	7.5	682.7	300	100	180.4	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9C3	120	60	3	3	7.5	682.7	350	100	177.65	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C9C4	120	60	3	3	7.5	682.7	450	100	175.23	383.82	332.5	0.867	150.4	140.8	150.4	159.2	137.1
C10C1	140	60	5	5	12.5	1196	275	100	327.69	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10C2	140	60	5	5	12.5	1196	300	100	328.13	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10C3	140	60	5	5	12.5	1196	350	100	328.9	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C10C4	140	60	5	5	12.5	1196	450	100	324.39	958.25	830	0.549	299.1	295.7	299.1	299.1	299.1
C11C1	160	70	5	5	12.5	1396	275	100	380.82	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C11C2	160	70	5	5	12.5	1396	300	100	380.49	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5

Specimen	Cross-section properties (mm)						Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	H (mm)	B (mm)	tw (mm)	tf (mm)	rm (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
C11C3	160	70	5	5	12.5	1396	350	100	377.96	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5
C11C4	160	70	5	5	12.5	1396	450	100	368.83	709.91	617.5	0.636	343.7	334.3	343.7	349.1	331.5

Annex C. I-sections results

Specimen	Cross-section properties (mm)					Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	bf (mm)	hw (mm)	tf (mm)	tw (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
I1M1	100	50	3	3	741	275	5	180.97	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1M3	100	50	3	3	741	300	5	181.89	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1M5	100	50	3	3	741	350	5	182.6	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1M7	100	50	3	3	741	450	5	185.14	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I2M1	100	50	2.5	3	642.5	275	5	145.15	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2M3	100	50	2.5	3	642.5	300	5	144.94	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2M5	100	50	2.5	3	642.5	350	5	145.15	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2M7	100	50	2.5	3	642.5	450	5	145.25	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I3M1	100	50	2	3	544	275	5	108.69	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3M3	100	50	2	3	544	300	5	109.3	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3M5	100	50	2	3	544	350	5	110.61	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3M7	100	50	2	3	544	450	5	111.93	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I4M1	80	40	3	3	591	275	5	152.86	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4M3	80	40	3	3	591	300	5	154.38	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4M5	80	40	3	3	591	350	5	158.24	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4M7	80	40	3	3	591	450	5	162.2	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I5M1	80	40	2.75	3	551.8	275	5	141.69	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5M3	80	40	2.75	3	551.8	300	5	142.91	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5M5	80	40	2.75	3	551.8	350	5	145.65	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3

Specimen	Cross-section properties (mm)					Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	bf (mm)	hw (mm)	tf (mm)	tw (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
I5M7	80	40	2.75	3	551.8	450	5	150.93	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I6M1	80	40	3.25	3	630.3	275	5	164.63	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6M3	80	40	3.25	3	630.3	300	5	165.44	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6M5	80	40	3.25	3	630.3	350	5	169.93	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6M7	80	40	3.25	3	630.3	450	5	179.32	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I7M1	80	40	3.5	3.5	687.8	275	5	180.85	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7M3	80	40	3.5	3.5	687.8	300	5	183.8	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7M5	80	40	3.5	3.5	687.8	350	5	190.54	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7M7	80	40	3.5	3.5	687.8	450	5	204.82	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I8M1	70	40	3.25	3.5	583.6	275	5	153.82	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8M3	70	40	3.25	3.5	583.6	300	5	156.98	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8M5	70	40	3.25	3.5	583.6	350	5	163.91	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8M7	70	40	3.25	3.5	583.6	450	5	177.48	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I9M1	70	40	3	3.5	549.5	275	5	143.52	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9M3	70	40	3	3.5	549.5	300	5	145.55	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9M5	70	40	3	3.5	549.5	350	5	151.95	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9M7	70	40	3	3.5	549.5	450	5	162.4	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I10M1	70	40	3.75	4	670	275	5	178.81	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10M3	70	40	3.75	4	670	300	5	183.8	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10M5	70	40	3.75	4	670	350	5	194.41	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10M7	70	40	3.75	4	670	450	5	213.08	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I11M1	100	80	5.5	4	1398	275	5	372.9	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5

Specimen	Cross-section properties (mm)					Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	bf (mm)	hw (mm)	tf (mm)	tw (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
I11M3	100	80	5.5	4	1398	300	5	382.35	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11M5	100	80	5.5	4	1398	350	5	396.83	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11M7	100	80	5.5	4	1398	450	5	429.8	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I12M1	100	80	6	4	1496	275	5	402.22	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12M3	100	80	6	4	1496	300	5	413.55	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12M5	100	80	6	4	1496	350	5	439.3	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12M7	100	80	6	4	1496	450	5	487.19	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I1M2	100	50	3	3	741	275	10	180.37	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1M4	100	50	3	3	741	300	10	180.67	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1M6	100	50	3	3	741	350	10	180.06	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1M8	100	50	3	3	741	450	10	179.96	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I2M2	100	50	2.5	3	642.5	275	10	147.07	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2M4	100	50	2.5	3	642.5	300	10	147.28	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2M6	100	50	2.5	3	642.5	350	10	147.07	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2M8	100	50	2.5	3	642.5	450	10	146.87	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I3M2	100	50	2	3	544	275	10	111.93	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3M4	100	50	2	3	544	300	10	111.72	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3M6	100	50	2	3	544	350	10	111.62	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3M8	100	50	2	3	544	450	10	111.12	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I4M2	80	40	3	3	591	275	10	152.45	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4M4	80	40	3	3	591	300	10	153.87	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4M6	80	40	3	3	591	350	10	153.57	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8

Specimen	Cross-section properties (mm)					Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	bf (mm)	hw (mm)	tf (mm)	tw (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
I4M8	80	40	3	3	591	450	10	157.63	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I5M2	80	40	2.75	3	551.8	275	10	137.94	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5M4	80	40	2.75	3	551.8	300	10	142	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5M6	80	40	2.75	3	551.8	350	10	143.22	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5M8	80	40	2.75	3	551.8	450	10	142.51	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I6M2	80	40	3.25	3	630.3	275	10	162.79	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6M4	80	40	3.25	3	630.3	300	10	164.93	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6M6	80	40	3.25	3	630.3	350	10	168.81	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6M8	80	40	3.25	3	630.3	450	10	175.44	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I7M2	80	40	3.5	3.5	687.8	275	10	180.03	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7M4	80	40	3.5	3.5	687.8	300	10	183.4	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7M6	80	40	3.5	3.5	687.8	350	10	189.72	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7M8	80	40	3.5	3.5	687.8	450	10	192.98	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I8M2	70	40	3.25	3.5	583.6	275	10	153.71	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8M4	70	40	3.25	3.5	583.6	300	10	157.28	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8M6	70	40	3.25	3.5	583.6	350	10	163.1	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8M8	70	40	3.25	3.5	583.6	450	10	172.69	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I9M2	70	40	3	3.5	549.5	275	10	143.22	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9M4	70	40	3	3.5	549.5	300	10	146.06	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9M6	70	40	3	3.5	549.5	350	10	151.13	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9M8	70	40	3	3.5	549.5	450	10	158.64	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I10M2	70	40	3.75	4	670	275	10	179.01	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5

Specimen	Cross-section properties (mm)					Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	bf (mm)	hw (mm)	tf (mm)	tw (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
I10M4	70	40	3.75	4	670	300	10	183.5	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10M6	70	40	3.75	4	670	350	10	193.7	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10M8	70	40	3.75	4	670	450	10	211.34	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I11M2	100	80	5.5	4	1398	275	10	372.7	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11M4	100	80	5.5	4	1398	300	10	382.15	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11M6	100	80	5.5	4	1398	350	10	394.88	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11M4	100	80	5.5	4	1398	450	10	426.1	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I12M2	100	80	6	4	1496	275	10	402.32	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12M4	100	80	6	4	1496	300	10	412.21	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12M6	100	80	6	4	1496	350	10	438.16	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12M8	100	80	6	4	1496	450	10	482.25	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I1C1	100	50	3	3	741	275	100	185.44	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1C2	100	50	3	3	741	300	100	184.63	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1C3	100	50	3	3	741	350	100	182.29	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I1C4	100	50	3	3	741	450	100	178.03	556.72	505	0.704	160.3	156.5	165.8	185.3	167.8
I2C1	100	50	2.5	3	642.5	275	100	158.44	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2C2	100	50	2.5	3	642.5	300	100	158.04	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2C3	100	50	2.5	3	642.5	350	100	156.31	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I2C4	100	50	2.5	3	642.5	450	100	152.55	433.92	392.5	0.798	125.7	125.3	130.7	157.8	135.7
I3C1	100	50	2	3	544	275	100	127.82	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3C2	100	50	2	3	544	300	100	127.51	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I3C3	100	50	2	3	544	350	100	126.6	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4

Specimen	Cross-section properties (mm)					Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	bf (mm)	hw (mm)	tf (mm)	tw (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
I3C4	100	50	2	3	544	450	100	124.98	312.99	325	0.877	95.4	97.1	99.9	125.9	108.4
I4C1	80	40	3	3	591	275	100	150.93	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4C2	80	40	3	3	591	300	100	151.34	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4C3	80	40	3	3	591	350	100	151.54	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I4C4	80	40	3	3	591	450	100	147.89	867.02	787.5	0.563	125.0	137.9	147.5	147.8	146.8
I5C1	80	40	2.75	3	551.8	275	100	140.17	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5C2	80	40	2.75	3	551.8	300	100	140.48	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5C3	80	40	2.75	3	551.8	350	100	139.87	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I5C4	80	40	2.75	3	551.8	450	100	136.21	769.15	700	0.598	111.6	124.7	133.8	137.9	134.3
I6C1	80	40	3.25	3	630.3	275	100	162.69	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6C2	80	40	3.25	3	630.3	300	100	163	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6C3	80	40	3.25	3	630.3	350	100	163.1	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I6C4	80	40	3.25	3	630.3	450	100	160.65	970.98	880	0.533	134.2	151.0	157.0	157.6	157.6
I7C1	80	40	3.5	3.5	687.8	275	100	179.01	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7C2	80	40	3.5	3.5	687.8	300	100	179.62	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7C3	80	40	3.5	3.5	687.8	350	100	180.85	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I7C4	80	40	3.5	3.5	687.8	450	100	181.15	1176.5	1073	0.483	118.0	158.8	161.0	171.9	171.9
I8C1	70	40	3.25	3.5	583.6	275	100	152.9	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8C2	70	40	3.25	3.5	583.6	300	100	153.31	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8C3	70	40	3.25	3.5	583.6	350	100	154.22	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I8C4	70	40	3.25	3.5	583.6	450	100	155.24	1350.99	1243	0.449	93.0	135.5	135.5	145.9	145.9
I9C1	70	40	3	3.5	549.5	275	100	142.51	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4

Specimen	Cross-section properties (mm)					Material		Numerical Results		CUFSM		Analytical resistance Nu,Rk				
	bf (mm)	hw (mm)	tf (mm)	tw (mm)	Ag (mm ²)	σ_u (MPa)	n	$N_{u,num}$ (kN)	$\sigma_{cr,num}$ (MPa)	σ_{crl} (Mpa)	λ_p	EC 1-1 (kN)	EC 1-4 (kN)	G&T (kN)	DSM (Carbon) (kN)	DSM (Stainless) (kN)
I9C2	70	40	3	3.5	549.5	300	100	143.12	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9C3	70	40	3	3.5	549.5	350	100	143.72	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I9C4	70	40	3	3.5	549.5	450	100	143.93	1212.57	1113	0.474	85.5	125.3	127.5	137.4	137.4
I10C1	70	40	3.75	4	670	275	100	177.58	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10C2	70	40	3.75	4	670	300	100	180.85	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10C3	70	40	3.75	4	670	350	100	181.66	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I10C4	70	40	3.75	4	670	450	100	183.4	1780.27	1640	0.390	65.8	137.9	137.9	167.5	167.5
I11C1	100	80	5.5	4	1398	275	100	369.51	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11C2	100	80	5.5	4	1398	300	100	373.83	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11C3	100	80	5.5	4	1398	350	100	376.19	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I11C4	100	80	5.5	4	1398	450	100	377.94	1479.73	1280	0.442	349.5	349.5	349.5	349.5	349.5
I12C1	100	80	6	4	1496	275	100	398.92	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12C2	100	80	6	4	1496	300	100	407.26	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12C3	100	80	6	4	1496	350	100	413.55	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0
I12C4	100	80	6	4	1496	450	100	419.11	1691.33	1460	0.414	374.0	374.0	374.0	374.0	374.0



Structural Applications of Ferritic Stainless Steels (SAFSS)
WP2: Structural performance of steel members

Recommendations for the use of Direct Strength Method

Authors: Petr Hradil, Asko Talja

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Summary <p>This report seeks to develop the necessary information which will enable comprehensive guidance on the use of Direct Strength Method for the design of ferritic stainless steel members. Direct Strength Method (DSM) is a modern simulation-based method developed specially for the design of thin-walled steel members, not yet included in the Eurocodes, but implemented in US and Australian design codes. The study addresses key factors which are required in order to demonstrate the performance of ferritic stainless steels e.g. in lattice roof trussed and space frame structures. The study is mainly based on modern numerical methods (particularly geometrically and materially non-linear analysis of the imperfect structure) to verify current closed-form or semi-numerical approaches. The necessary steps to develop design recommendations using the DSM are proposed. DSM may be an alternative approach included in an appendix to EN 1993-1-4 in the future.</p>		
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Written by  Petr Hradil Research Scientist	Reviewed by  Asko Talja Senior Research Scientist	Accepted by  Eila Lehmus Technology Manager
VTT's contact address P.O. Box 1000, FI-02044 VTT, Finland		
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Preface

Direct Strength Method (DSM) is a modern simulation-based method developed specially for the design of thin-walled steel members, not yet included in the Eurocodes, but implemented in US and Australian design codes. The method is predicated upon the idea that if an engineer determines all of the elastic instabilities for the member and its gross section (i.e. local, distortional, and global buckling) and the load (or moment) that causes the section to yield, then the strength can be directly determined. A geometrically and materially non-linear with imperfections analysis (GMNIA) is used to provide data for comparison with the current methods and DSM calculations.

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Authors

Contents

Preface	2
Abbreviations	4
Related standards	4
1 Introduction	5
2 Member resistance	5
2.1 Ayrton-Perry formula	5
2.2 Tangent modulus approach	6
2.3 Combined Ayrton-Perry formula and tangent modulus approach ..	6
2.4 North American specification AISI S100-2007	6
3 Cross-section resistance	7
3.1 Effective cross-section	7
3.2 Direct strength method	7
3.3 Modified Direct Strength Method	10
4 Elastic buckling solutions	10
4.1 Finite Element Method	11
4.2 Finite Strip Method	11
4.3 Generalized Beam Theory	11
4.4 Manual methods	11
5 Virtual buckling tests	12
5.1 Cross-sections and material	12
5.2 Initial imperfections	13
5.3 Ultimate loads	13
6 Comparison of the design methods	14
6.1 Section A results	15
6.2 Section B results	18
7 Discussion	21
8 Conclusions	21
8.1 Effective Width Method	21
8.2 Direct Strength Method	22
9 Recommendations	22
References	23
Appendix A: DSM limits for pre-qualified members	26
Appendix B: Closed-form elastic buckling solutions	29
Appendix C: Example calculations of studied cross-sections	31

Abbreviations

AISI	American Iron and Steel Institute
ASCE	American Society of Civil Engineers
AS/NZS	Australian Standard/New Zealand Standard
CEN	European Committee for Standardization
CSM	Continuous Strength Method
DSM	Direct Strength Method
EN	European Standards
FB	Flexural buckling
FEM	Finite Element Method
FSM	Finite Strip Method
GBT	Generalized Beam Theory
GMNIA	Geometrically + materially nonlinear analysis with imperfections
LEA	Linear Eigenvalue Analysis
LTB	Lateral-torsional buckling
TB, TFB	Torsional buckling, Torsional-flexural buckling

Related standards

AISI S100-2007	North American Specification for the Design of Cold-Formed Steel Structural Members (AISI, 2007)
AISI S100-2007-C	Commentary on North American Specification for the Design of Cold-Formed Steel Structural Members (AISI, 2007)
AS/NZS 4600:2005	Australian/New Zealand Standard™ Cold-formed steel structures (AS/NZS, 2005)
AS/NZS 4673:2001	Australian/New Zealand Standard™ Cold-formed stainless steel structures (AS/NZS, 2001)
EN 1993-1-1	Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings (CEN, 2006)
EN 1993-1-3	Eurocode 3: Design of steel structures – Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting (CEN, 2006)
EN 1993-1-4	Eurocode 3: Design of steel structures – Part 1-4: General rules - Supplementary rules for stainless steels (CEN, 2006)
EN 1993-1-5	Eurocode 3: Design of steel structures – Part 1-5: Plated structural elements (CEN, 2006)
SEI/ASCE 8-02	Specification for the Design of Cold-Formed Stainless Steel Structural Members (SEI/ASCE 2002)

1 Introduction

The Direct Strength Method (DSM), an alternative calculation of cold-formed steel resistance of members, taking into account the interactions of local, distortional and overall buckling. It has been introduced in American and Australian/New Zealand standards AISI S100 and AS/NZS 4600 based on [1–4].

The detailed overview of design methods used in current standards that are proposed for the use in evaluation of cross-section and member resistance is presented in the “Review of available data” report [5]. The background for the local buckling calculation is included in Appendix C of this report. This section will mostly focus on the description of DSM and methods connected to DSM.

The calculation methods presented below are deliberately written in the form of design rules in EN 1993. Therefore the nominal buckling resistance N_b is used instead of axial strength P_n from ASCE 8-02 and AISI S100 specification or nominal member capacity N_c from AS/NZS 4600 and 4673. The critical buckling length L_{cr} equals to the KL term in AISI/ASCE specification and kl term in AS/NZS. The nondimensional slenderness λ and the radius of gyration r from AISI/ASCE specification and AS/NZS are written as $\bar{\lambda}$ and i respectively according to the form used in EN.

2 Member resistance

The nominal member resistances of columns and beams in Eq. (1) are reduced cross-sectional resistances Af_y and Wf_y respectively.

$$\begin{aligned} N_b &= \chi Af_y \text{ for columns} \\ M_b &= \chi Wf_y \text{ for beams.} \end{aligned} \quad (1)$$

The reduction factors χ are not used in ASCE and AS/NZS standards, where the reduced member strength is calculated directly.

2.1 Ayrton-Perry formula

The buckling strength reduction χ can be calculated by the formula proposed by Ayrton and Perry [6] that is represented in Eqs. (2) and (3) in a form used in EN 1993 where N_{cr} and M_{cr} are the elastic buckling loads.

$$\chi = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}^2}} \quad (\leq 1) \quad (2)$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} \text{ for columns and } \bar{\lambda} = \sqrt{\frac{Wf_y}{M_{cr}}} \text{ for beams.} \quad (3)$$

The calculation of coefficient φ recommended by EN 1993 is based on two parameters α and $\bar{\lambda}_0$ (Eq. (4)) that are calibrated by the experiments for different buckling modes and cross-sections.

$$\varphi = 0,5 \left[1 + \alpha (\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2 \right] \quad (4)$$

Four parameters α , β , $\bar{\lambda}_0$ and $\bar{\lambda}_1$ are required by the alternative method of AS/NZS 4673 (see Eq. (5)), and therefore the buckling curve can describe more accurately materials with rounded stress-strain relationship.

$$\varphi = 0,5 \left(1 + \eta + \bar{\lambda}^2 \right) \text{ and } \eta = \alpha \left[(\bar{\lambda} - \bar{\lambda}_1)^\beta - \bar{\lambda}_0 \right]. \quad (5)$$

2.2 Tangent modulus approach

The tangent method in ASCE 8-02 specification and AS/NZS 4673 is based on the iterative calculation of critical buckling strength of materials with Ramberg-Osgood constitutive model [7]. Here it is represented in the form compatible with EN 1993 in Eqs. (6) and (7) where n stands for the nonlinear factor from the Ramberg-Osgood model.

$$\chi = \frac{1}{\bar{\lambda}^2} \quad (\leq 1). \quad (6)$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} \sqrt{1 + 0.002n \frac{E}{f_y} \chi^{n-1}} \text{ for columns} \quad (7)$$

$$\bar{\lambda} = \sqrt{\frac{Wf_y}{M_{cr}}} \sqrt{1 + 0.002n \frac{E}{f_y} \chi^{n-1}} \text{ for beams.}$$

2.3 Combined Ayrton-Perry formula and tangent modulus approach

The use of nondimensional slenderness calculated by the tangent method in Eq. (7) in Ayrton-Perry formula (Eq. (2)) was proposed by Hradil et al. [8]. It accounts for the initial imperfections and gradual yielding at the same time. The method requires iterative calculations in the same way as the original tangent method.

2.4 North American specification AISI S100-2007

The AISI S100 specification for the design of cold-formed steel structural members provides rules generally applicable to carbon steels. The method is, however, noted herewith because the AISI specification includes also DSM curves for the interaction of local and overall buckling that are compatible with the Eq. (8).

$$\chi = \begin{cases} 0,658 \bar{\lambda}^2 & \text{for } \bar{\lambda} \leq 1,5 \\ \frac{0,877}{\bar{\lambda}^2} & \text{for } \bar{\lambda} > 1,5 \end{cases} \text{ for columns} \quad (8)$$

$$\chi = \begin{cases} 1 & \text{for } \bar{\lambda} \leq 0,6 \\ 1,11 - 0,309\bar{\lambda} & \text{for } 1,6 > \bar{\lambda} \leq 1,34 \text{ for beams.} \\ \frac{1}{\bar{\lambda}^2} & \text{for } \bar{\lambda} > 1,34 \end{cases}$$

3 Cross-section resistance

3.1 Effective cross-section

The method for evaluation of local buckling used in current EN 1993 is based on reduction of the cross-sectional area of Class 4 cross-sections by omitting parts of the section that are subjected to local buckling and which are thus ineffective in overall member resistance. The effect of distortional buckling of stiffeners is accounted for by reducing the thickness of outstanding parts of the effective section. The resulting cross-section may have shift in centroid position leading to the combination of compression and bending. Iterative calculations are needed for the effective width of plates subjected to bending due to the shift of section centroid and also due to the reduced thickness of outstanding stiffeners of open sections.

$$\begin{aligned} N_b &= \chi A_{eff} f_y \text{ for columns} \\ M_b &= \chi W_{eff} f_y \text{ for beams.} \end{aligned} \tag{9}$$

This effective cross-section approach is employed in EN 1993, AISI S100, ASCE 8-02, AS/NZS 4600 and 4673. However, there are fundamental differences in the standards:

- (a) The effective section is independent on the overall buckling resistance and the plate slenderness is based on the yield strength f_y and the critical stress σ_{cr} as in Eq. (10). Then the reduction factor χ for member buckling is calculated from these effective section properties. This method is used in EN 1993.

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}}. \tag{10}$$

- (b) The member buckling resistance for overall buckling is calculated using the full cross-section. Then the effective section is calculated using the member buckling stress χf_y (Eq. (11)). This method is employed in AISI/ASCE and AS/NZS standards. It was also recommended for the Eurocode by Talja and Salmi [9] already in 1994.

$$\bar{\lambda}_p = \sqrt{\frac{\chi f_y}{\sigma_{cr}}}. \tag{11}$$

3.2 Direct strength method

The basics of the Direct Strength Method (DSM) are described in [5]. This method was recently included in the North American and Australian standards for

carbon steel cold formed members AISI S100 and AS/NZS 4600. Its modification for stainless steels was proposed by Becque et al. [10] in combination with all major stainless steel design standards including the Eurocode. In this method, the reduced member strength f is calculated directly from the strength curves. These curves are defined in AISI S100 and AS/NZS 4600 standards in a form similar to Equation (12).

$$f = \begin{cases} f_y & \text{for } \lambda \leq \lambda_{\lim} \\ K_1 - K_2 \left(\frac{\sigma_{cr}}{f_y} \right)^{K_3} \left(\frac{\sigma_{cr}}{f_y} \right)^{K_4} f_y & \text{for } \lambda > \lambda_{\lim} \end{cases}, \text{ where } \lambda = \sqrt{\frac{f_y}{\sigma_{cr}}}. \quad (12)$$

The Equation (12) can be written also as Equation (13) provided that $C_1 = K_1$, $C_2 = K_2$, $C_3 = 2K_4$ and $C_4 = 2(K_3 + K_4)$. We will use Eq. (13) in this report, which is more consistent with the original theories.

$$f = \begin{cases} f_y & \text{for } \lambda \leq \lambda_{\lim} \\ \left(\frac{C_1}{\lambda^{C_3}} - \frac{C_2}{\lambda^{C_4}} \right) f_y & \text{for } \lambda > \lambda_{\lim} \end{cases}, \text{ where } \lambda = \sqrt{\frac{f_y}{\sigma_{cr}}}. \quad (13)$$

Currently, the method covers distortional buckling and local-overall buckling interaction in compression or bending. The interaction of local and distortional buckling and distortional and overall buckling is considered insignificant, and therefore is not included in the current DSM formulation [2]. The rules for shear buckling and combined shear and bending were recently proposed by Pham and Hancock [11].

The Direct Strength Method use is limited to pre-qualified column and beam cross-sections. They include lipped C-sections, lipped C-sections with web stiffener(s), Z-sections, hats, racks upright (only compression) and trapezoids (only bending). The geometric and material limits of those sections recommended by AISI S100 and AS/NZS 4600 are presented in Appendix A. Cold-formed sections that do not satisfy the limits can still be used with additional penalization presented in the codes.

(a) Local and overall buckling interaction

The interaction of local (plate) buckling and overall (member) buckling can be calculated by DSM as the reduction of member strength in Eq. (14). The reduction factor of member buckling χ is discussed in previous chapters.

$$\begin{aligned} N_b &= \chi A f_l \text{ for columns} \\ M_b &= \chi W f_l \text{ for beams.} \end{aligned} \quad (14)$$

The calculation in Eq. (15) is based on the knowledge of the overall buckling reduction factor χ and the critical local buckling stress $\sigma_{cr,l}$ that can be obtained for instance by the Finite Strip Method (FSM) or manually by Eq. (16), as recommended by AISI S100. The manual method is, however, providing poor prediction since it does not account for the interaction between elements.

$$f_l = \begin{cases} f_y & \text{for } \lambda_l \leq \lambda_{l,lim} \\ \left(\frac{C_1}{\lambda_l^{C3}} - \frac{C_2}{\lambda_l^{C4}} \right) f_y & \text{for } \lambda_l > \lambda_{l,lim} \end{cases}, \text{ where } \lambda_l = \sqrt{\frac{\chi f_y}{\sigma_{cr,l}}}. \quad (15)$$

$$\sigma_{cr,l} = k \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b} \right)^2 \text{ for each plate element.} \quad (16)$$

The parameters C_1 to C_4 and $\lambda_{l,lim}$, recommended by Becque et al. [10] and Bezkorovainy et al. [12], are presented in Table 1 to be used with different standardized overall buckling calculation methods. It should be noted that parameters by Bezkorovainy et al. [12] were obtained from the plate buckling analysis and have a poor match to the real cross-sectional behaviour because they do not account for the corner areas of cold-formed profiles.

Table 1. DSM parameters for interaction of overall and local buckling of members.

	C_1	C_2	C_3	C_4	$\lambda_{l,lim}$
Johnson and Winter [13]	1.00	0.22	1.0	2.0	0.673
Bezkorovainy et al. [12]	0.90	0.20	1.0	2.0	0.500
Becque et al. (EN 1993-1-4) [10]	0.95	0.22	1.0	2.0	0.550
Becque et al. (AS/NZS 4673) [10]	0.95	0.22	0.8	1.6	0.474
Becque et al. (ASCE 8-02) [10]	0.90	0.20	0.9	1.8	0.463
AISI S100, AS/NZS 4600 [14, 15]	1.00	0.15	0.8	1.6	0.776

(b) Distortional buckling

In AISI S100 and AS/NZS 4600, DSM also offers a method for calculation of distortional buckling resistance. It can be written as a reduction of member strength – so the Eq. (17) will be similar to the basic formula from EN 1993.

$$N_b = Af_d \text{ for columns} \quad (17)$$

$$M_b = Wf_d \text{ for beams.}$$

The calculation of reduced strength in Eq. (18) is based on the knowledge of the critical distortional buckling stress $\sigma_{cr,d}$ that can be obtained for instance by the Finite Strip Method (FSM).

$$f_d = \begin{cases} f_y & \text{for } \lambda_d \leq \lambda_{d,lim} \\ \left(\frac{C_1}{\lambda_d^{C3}} - \frac{C_2}{\lambda_d^{C4}} \right) f_y & \text{for } \lambda_d > \lambda_{d,lim} \end{cases}, \text{ where } \lambda_d = \sqrt{\frac{f_y}{\sigma_{cr,d}}}. \quad (18)$$

The parameters C_1 to C_4 and $\lambda_{d,lim}$ recommended by Becque et al. [10] are presented in Table 2 to be used with different stainless steel grades. The values used in AISI S100 are also included in the table.

Table 2. DSM parameters for distortional buckling.

	C_1	C_2	C_3	C_4	$\lambda_{d,lim}$
Austenitic steels [10]	0.80	0.15	1.1	2.2	0.533
Ferritic steels [10]	0.90	0.20	1.1	2.2	0.533
AISI S100	1.00	0.25	1.2	2.4	0.561
AS/NZS 4600	1.00	0.22	1.0	2.0	0.673

3.3 Modified Direct Strength Method

The method by Becque et al. [10] was further improved for the low slenderness range by Rossi and Rasmussen [16].

(a) Local buckling

The calculation of local buckling (without overall buckling interaction) in Eq. (19) is, however, valid only with the limit member slenderness of 0,474 for AS/NZS rules (Table 2).

$$f_l = \left[\left(1 - 2,11\lambda_l \right) \left(\frac{f_u}{f_y} - 1 \right) \right] f_y \quad \text{for } \lambda_l \leq \lambda_{l,lim}. \quad (19)$$

(b) Local-overall buckling interaction

The modification of overall buckling reduction of AS/NZS rules (Eqs. (2), (3) and (5)) is recommended in the case of overall and local buckling interaction (see Eqs. (20) and (21)). No further modification is then needed and the Eq. (15) can be used in its original form.

$$\chi = \left(1 - \frac{\bar{\lambda}}{\bar{\lambda}_{lim}} \right) \left(\frac{f_u}{f_y} - 1 \right) + 1 \quad \text{for } \bar{\lambda} \leq \bar{\lambda}_{lim}. \quad (20)$$

$$\bar{\lambda}_{lim} = \bar{\lambda}_0^{1/\beta} + \bar{\lambda}_1. \quad (21)$$

(c) Distortional buckling

The modified formula for distortional buckling (Eq. (18)) can be used for both, austenitic and ferritic steels (see Eq. (22)).

$$f_d = \left[\left(1 - 1,88\lambda_d \right) \left(\frac{f_u}{f_y} - 1 \right) \right] f_y \quad \text{for } \lambda_d \leq \lambda_{d,lim}. \quad (22)$$

4 Elastic buckling solutions

Presented methods rely on the knowledge of elastic buckling critical stress or critical load. While manual methods for overall buckling of members are successfully used in member design for many decades, the elastic buckling solutions for local or distortional buckling of cross-sections are more complex phenomena and usually require numerical approach.

4.1 Finite Element Method

Cold-formed members are usually modelled using finite shell elements that are supported by most of the commercial FE solvers. The finite element model has to be prepared carefully taking into account proper element type, its shape function, mesh size and element aspect ratio. The benchmark test with different settings is often recommended before the final FE analysis.

The elastic buckling can be then solved by the linear eigenvalue analysis (LEA), searching for the elastic critical loads. This method, however, cannot distinguish between local, distortional and overall modes unless special constraints are included in the model. Moreover, the number of required eigenmodes is not known before the desired failure is reached. Designers usually have to calculate many values and then search manually for the first applicable buckling mode.

It is possible to suppress local and distortional buckling modes in the buckling analysis by stiffening each cross section with membrane elements [17]. This function is not usually available in FE programs, but it was recently implemented in the Abaqus plug-in developed in VTT [18]. Multipoint constraints were used to prevent overall and distortional modes by Kumar and Kalyanaraman [19]. Such approaches can greatly help the designers with selection of the proper buckling mode because the desired eigenvalue is usually the first one calculated.

In our study we used Abaqus solver [20] and S9R5 quadratic thin shell elements with reduced integration, which proved to provide acceptable results and their shape function is suitable also for modelling of cold-formed corners.

4.2 Finite Strip Method

The method particularly suitable for identifying cross-sectional critical loads is implemented in several commercial and open-source software products. It is very fast and it can generate so called signature curve, where the minimum critical loads for local or distortional buckling may be identified easily. There are several similarities with the FEM especially in the modelling phase. Cross-section has to be properly partitioned and at least two elements per face are recommended. The corner areas may require finer mesh as well as in FEM calculations.

In our study we used open-source software CUFSM [21]. The handling of inputs and outputs was automated by the Python script using the Matlab import/export module.

4.3 Generalized Beam Theory

The GBT is relatively new method and only the limited selection of programs using GBT is available. One example is GBTUL software. Even though the method is not used in this report, we encourage readers to read additional information about this theory [22, 23].

4.4 Manual methods

The closed-form solutions are usually very efficient and simple to use. They do not require special software and even though these methods provide conservative results they are very popular in engineering community and form the basic

structure of current design codes. The manual methods are discussed in more detail in Appendix B.

5 Virtual buckling tests

Finite element models were used to simulate the buckling experiments on cold-formed lipped channels. The problem of additional bending effect due to the shift of effective centroid in singly symmetric sections was solved by fixing the model ends as recommended in [24]. Therefore the real length L of tested columns was always two times higher than the critical buckling length in flexural and torsional buckling ($L_{cr} = L_{cr,x} = L_{cr,y} = L_{cr,T} = \frac{1}{2}L$).

5.1 Cross-sections and material

The cross-sectional shapes were designed to fail in overall torsional-flexural buckling (Section A) and flexural buckling (Section B) as in Figure 1 and Table 4. Section B was also designed to slightly violate DSM limits of the pre-qualified sections (Table 4 and Appendix A) to study the effect of long and slender element (the lip) on the critical section load. The average corner radius is 3 mm.

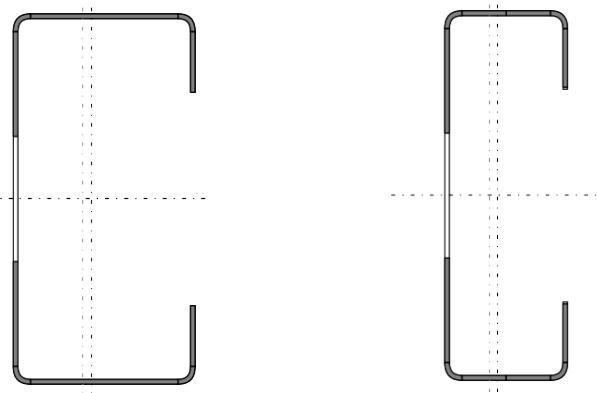


Figure 1. Studied cross-sections: Section A (left) and Section B (right).

Table 3. Cross-sectional parameters.

	h_0	b_0	D	θ	t
Section A	72 mm	36 mm	15 mm	90°	0.5 to 1.5 mm
Section B	72 mm	24 mm	15 mm	90°	0.5 to 1.5 mm

The finite element method was using Ramberg-Osgood material model [7] with the n factor equal to 10, yield strength $f_y = 250$ MPa and the initial modulus of elasticity $E_0 = 200$ GPa.

Table 4. Geometric and material limits for the use with AISI, ASCE and AS/NZS standards.

	Section A	Pre-qualified column	beam	Section B	Pre-qualified column	beam
h_0/t	48 to 144	OK	OK	48 to 144	OK	OK
b_0/t	24 to 72	OK	OK	16 to 48	OK	OK
D/t	10 to 30	OK	OK	10 to 30	OK	OK
h_0/b_0	2	OK	OK	3	OK	OK
D/b_0	0.41	OK	OK	0.62	-	OK
θ	90°	OK	OK	90°	OK	OK
E/f_v	800	OK	OK	800	OK	OK

5.2 Initial imperfections

The ultimate loads recorded in Table 5 and Table 6 are produced by the virtual testing tool [18], where the initial imperfections were combined from the overall and local component. The distribution of overall and local imperfection was provided by the tool automatically from the linear eigenvalue analysis. The magnitude of overall imperfections was $L/1500$ in case of columns failing in overall buckling or local-overall interaction. In the case of local imperfections, we used Dawson and Walker's formula [25] in Equation (23), where t is the plate thickness, σ_{cr} is the plate critical stress and σ_{02} is the 0,2% offset yield strength of the material.

$$w_0 = 0,023t(\sigma_{02}/\sigma_{cr}) \quad (23)$$

It should be noted that the amplitude of overall imperfections may be unproportionally higher than of local imperfections even for short columns where the local buckling is clearly dominating. However, the design codes do not provide guidance about the limit column lengths for local-overall interaction. Therefore we have reduced the overall amplitude proportionally to the critical stress ratio $\sigma_{cr}/\sigma_{cr,l}$ of the member and the cross-section in the case of short columns.

5.3 Ultimate loads

(a) columns failing in overall torsional-flexural buckling

Table 5. Ultimate loads (in kN) of FEM Section A in compression.

L_{cr} (mm)	0.5	0.75	1.0	1.25	1.5
125	9.692	20.455	33.452	43.821	59.494
250	9.409	20.319	30.794	43.730	59.118
500	9.673	18.498	29.609	43.266	52.642
750	9.394	19.458	29.097	39.928	48.085
1000	9.525	18.313	27.757	35.018	42.340
1250	8.811	16.131	23.328	29.507	35.996
1500	7.573	13.541	18.509	23.918	29.736
2000	4.699	8.399	11.780	15.538	19.777
3000	2.718	4.963	6.984	9.265	10.801

(b) columns failing in overall flexural buckling

Table 6. Ultimate loads (in kN) of FEM Section B in compression.

L_{cr} (mm)	t (mm)				
	0.5	0.75	1.0	1.25	1.5
125	9.393	17.991	26.771	35.845	50.860
250	9.136	17.392	25.578	34.487	48.640
500	9.009	15.932	24.470	32.706	42.902
750	8.230	14.267	23.060	30.158	36.800
1000	7.001	12.474	19.030	24.888	30.299
1250	4.600	n/a	14.362	n/a	23.586
1500	4.389	n/a	10.636	n/a	16.357
2000	2.719	n/a	6.492	n/a	9.767
3000	1.244	n/a	2.992	n/a	4.497

6 Comparison of the design methods

The following four methods are compared in this document:

- | | |
|--------------------|--|
| CSM | The continuous strength method in its latest form [26] is used only for section resistance calculations since it does not cover overall buckling. |
| EN 1993-1-1 | The calculation of resistance of carbon steel members resistance. It is also based on EN 1993-1-3 and EN 1993-1-5. |
| EN 1993-1-4 | The standard procedure for calculation of stainless steel member resistance is the modification of the EN 1993-1-1 method. It uses specific member buckling curves, section classification limits and reduction factor for local buckling. |
| EN Talja and Salmi | The calculation of local-overall buckling interaction according to EN 1993-1-4 method is modified so that the full section area is used in the member buckling reduction and real stress is used in the effective section calculation as recommended by Talja and Salmi [9]. |
| DSM-EN | Direct strength method recommended by Becque et al. (for ferritic stainless steels) combined with EN 1993-1-4 member buckling curves. The critical stress of the cross-section is calculated manually. |
| DSM-EN-FSM | Direct strength method recommended by Becque et al. combined with EN 1993-1-4 overall buckling curves. The critical stress for local and distortional buckling is obtained from CUFSM software [27]. This method was used only in member resistance calculations for selected cross-sections and variable member length. |

The design methods were compared with the results of the FEM study. Because of the relatively short calculation times, the member lengths and material thicknesses were varying continuously in small steps to achieve smooth curves as results. The lengths of studied columns were from 50 to 4000 mm and the material thicknesses were from 0.5 to 2.0 mm. The material model was assumed elastic-plastic with the n factor equal to 10. Modulus of elasticity of 200 GPa and yield strength of 250 MPa were applied. For the CSM method, the material model was extended to a bi-linear form with the ultimate strength of 350 MPa.

The following sections show the results of this parametric study as member resistances plotted against (a) critical length or (b) material thickness. The same graphs are also presented in the nondimensional form, where the resistances divided by cross-sectional resistance $A_f y$ are plotted against (a) member slenderness or (b) section slenderness. Design methods are compared to the FEM results (red markers in Figure 2 to Figure 11). The points named “local-overall interaction” indicate the critical length or the thickness, where the overall critical stress is equal to the local buckling critical stress.

6.1 Section A results

(a) Columns with variable length and fixed thickness to 0.5, 1.0 and 1.5 mm

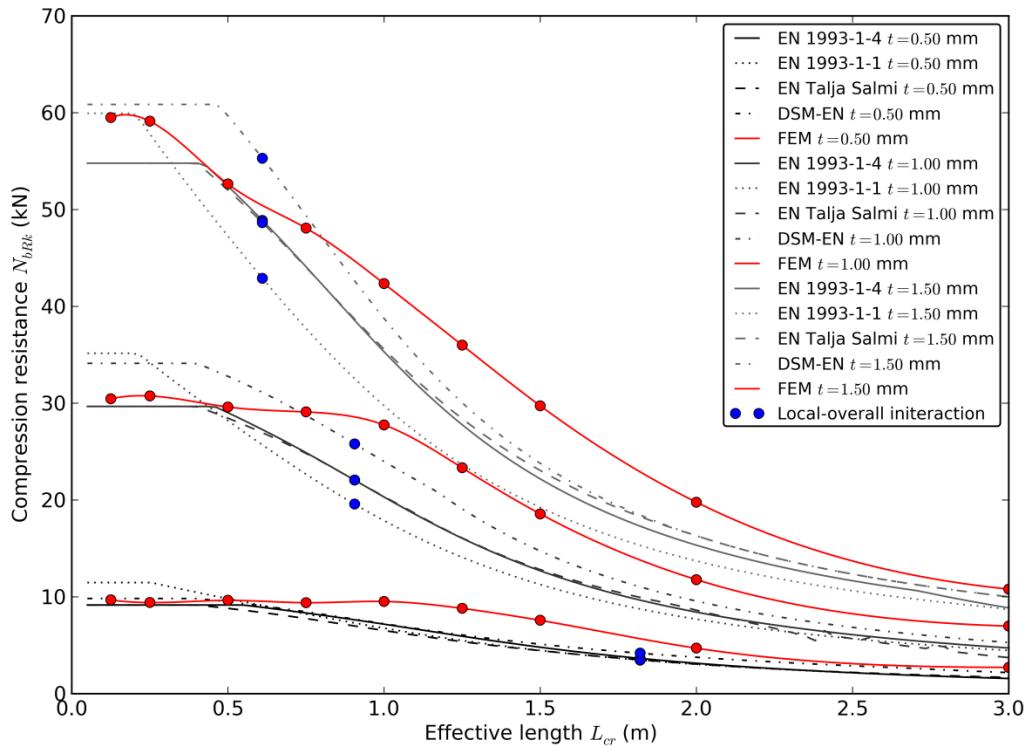


Figure 2. Compression resistance of Section A with variable length.

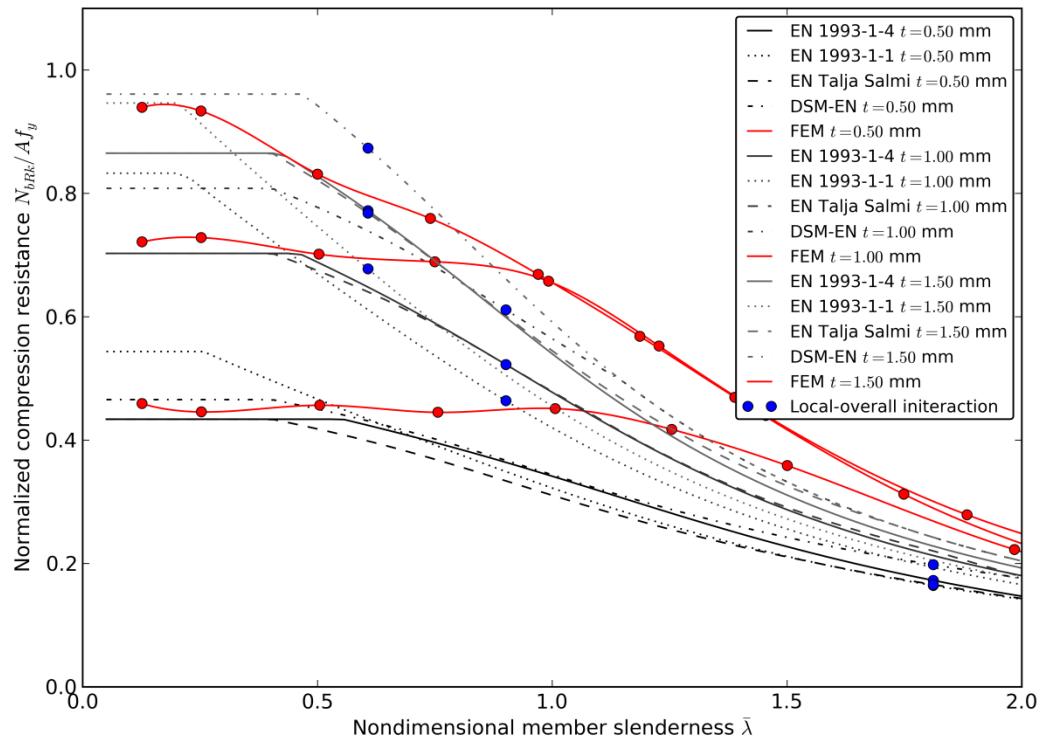


Figure 3. Nondimensional compression resistance of Section A with variable member slenderness.

(b) Columns with variable thickness and fixed length to 0.5, 0.75 and 1.0 m

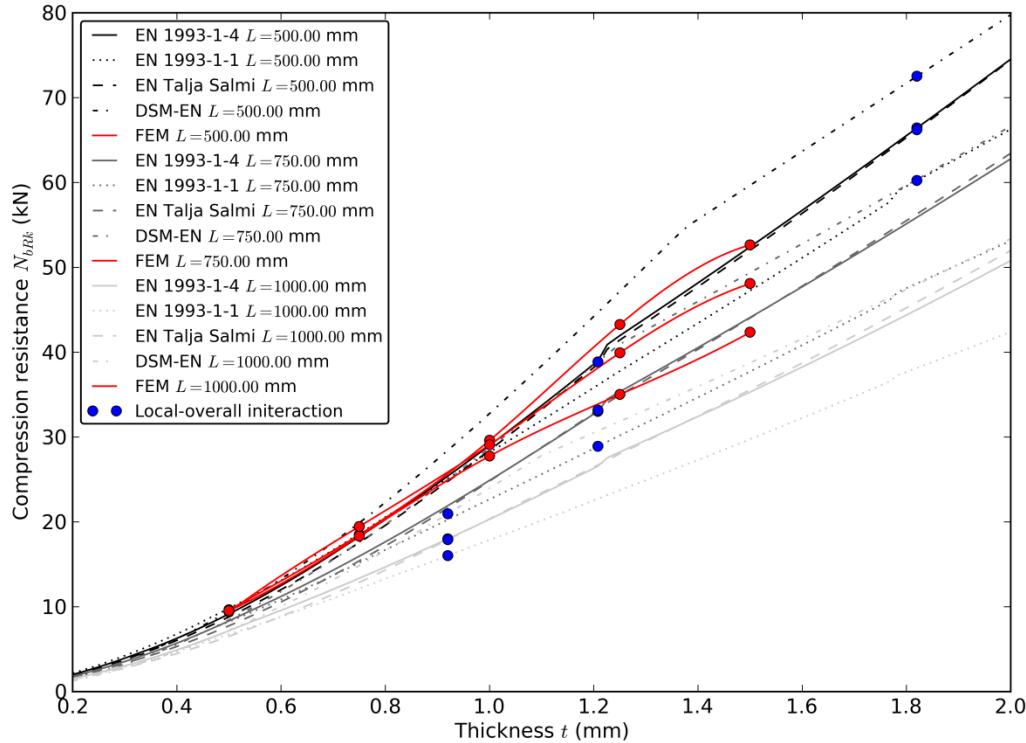


Figure 4. Compression resistance of Section A with variable thickness.

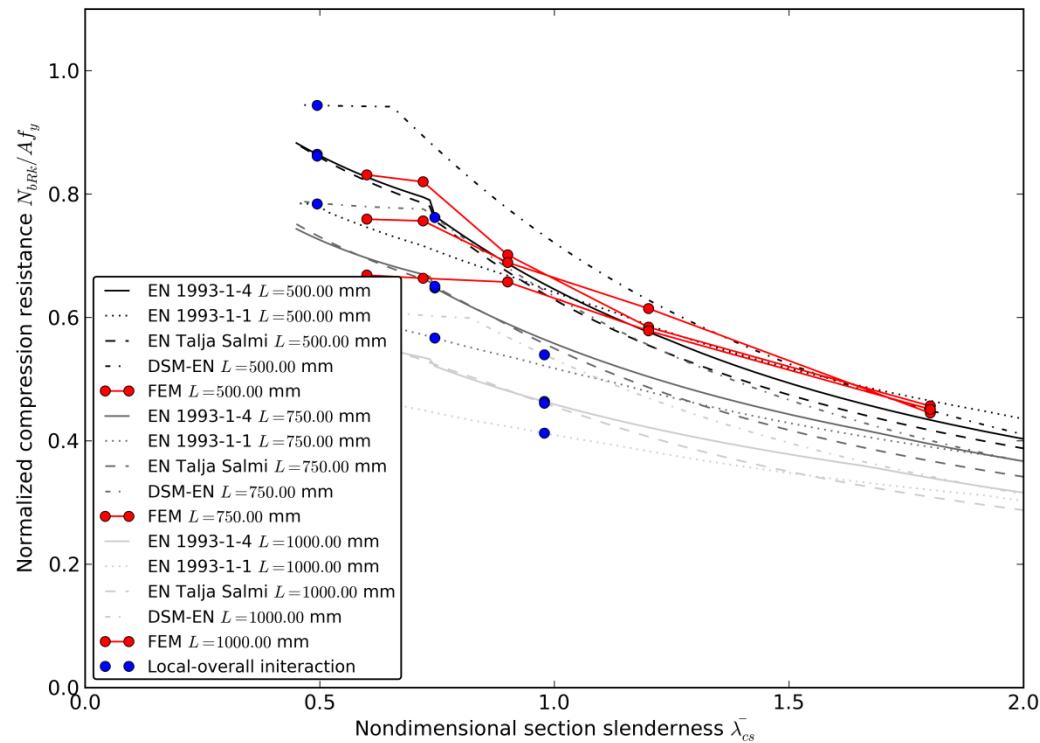


Figure 5. Nondimensional compression resistance of Section A with variable section slenderness.

(c) Comparison to FEM results

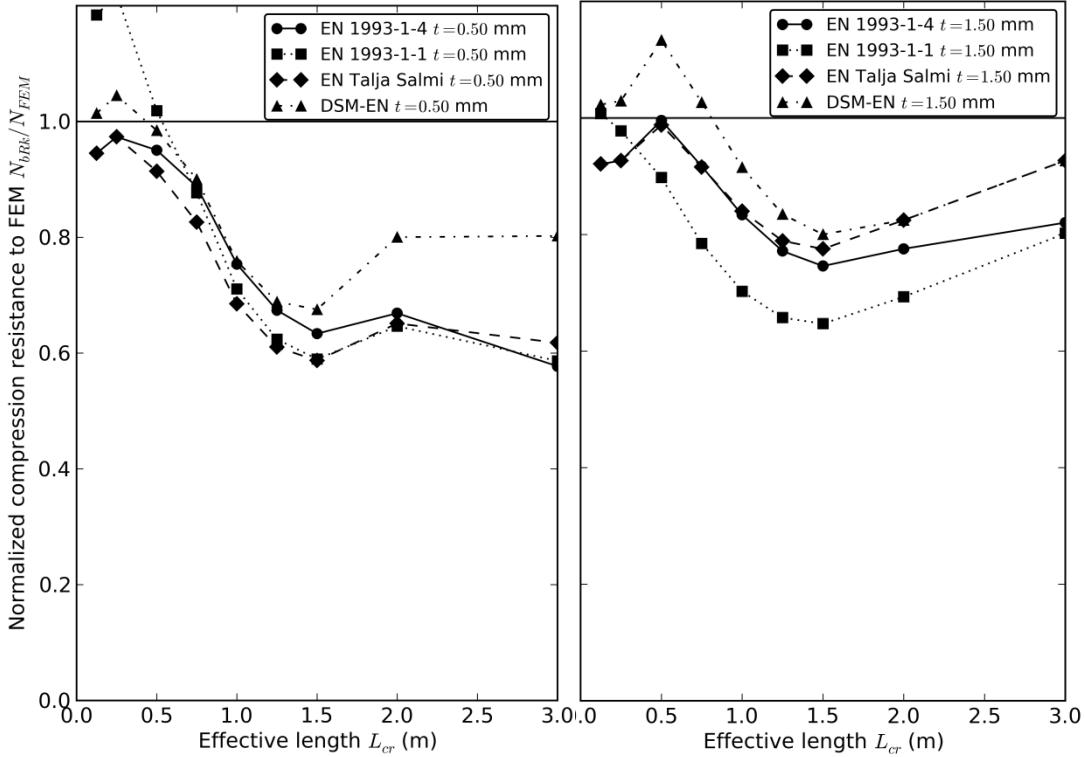


Figure 6. Compression resistance normalized to FEM results with respect to the variable length.

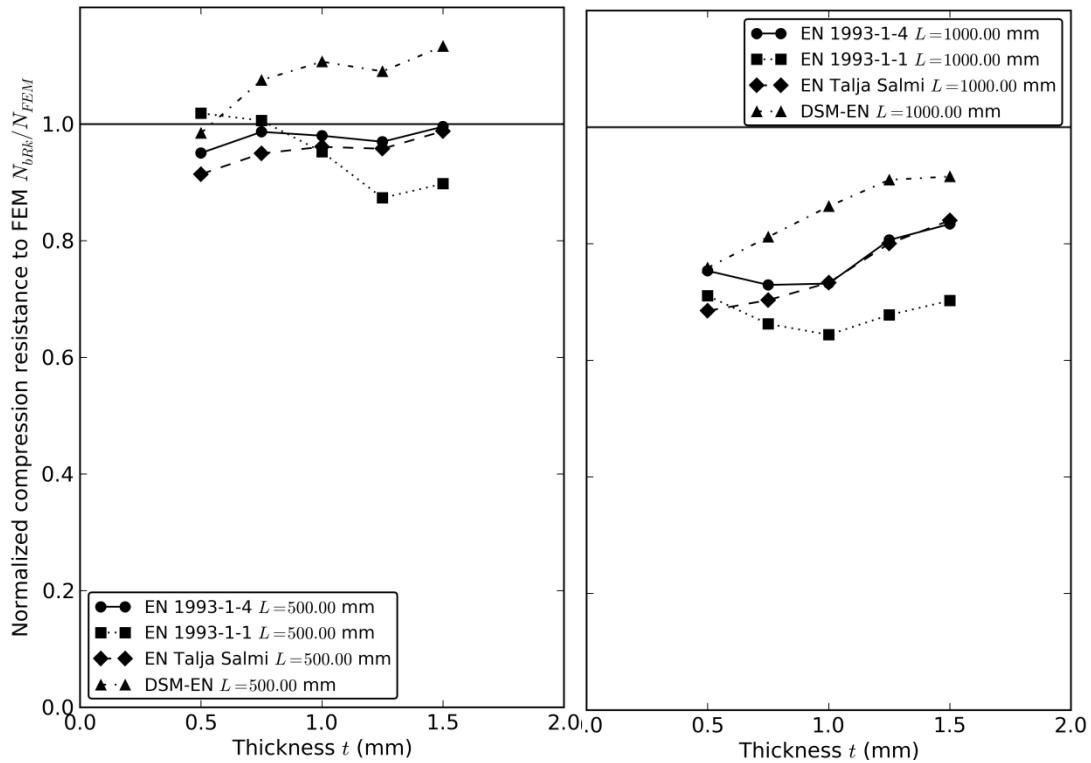


Figure 7. Compression resistance normalized to FEM results with respect to the variable thickness.

6.2 Section B results

(a) Columns with variable length and fixed thickness to 0.5, 1.0 and 1.5 mm

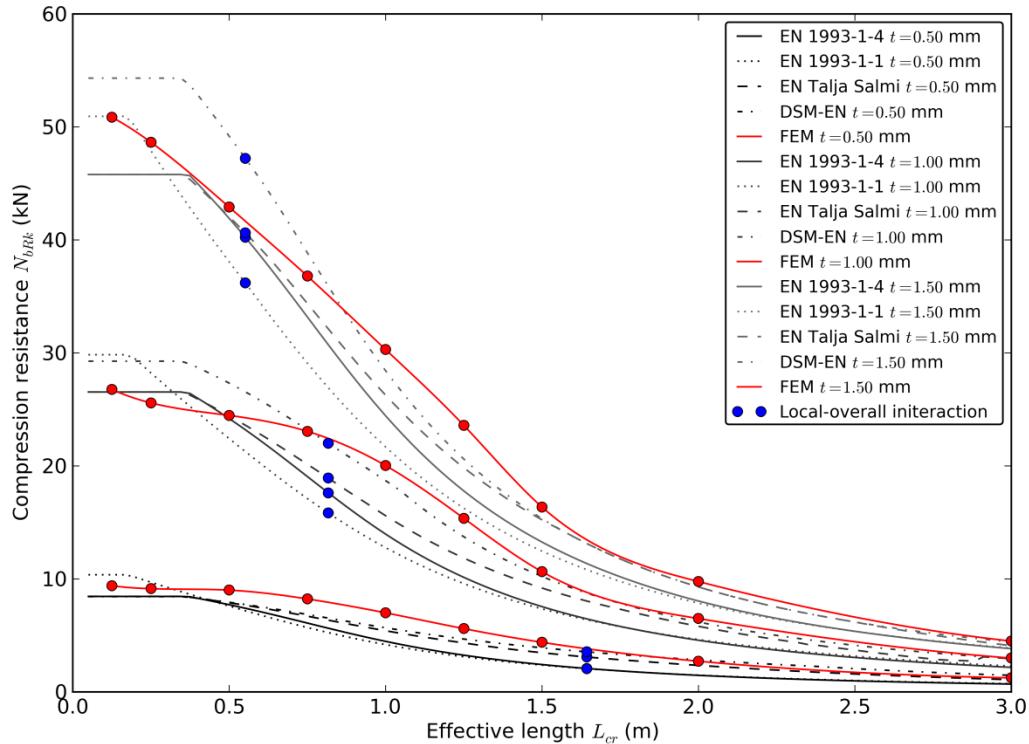


Figure 8. Compression resistance of Section B with variable length.

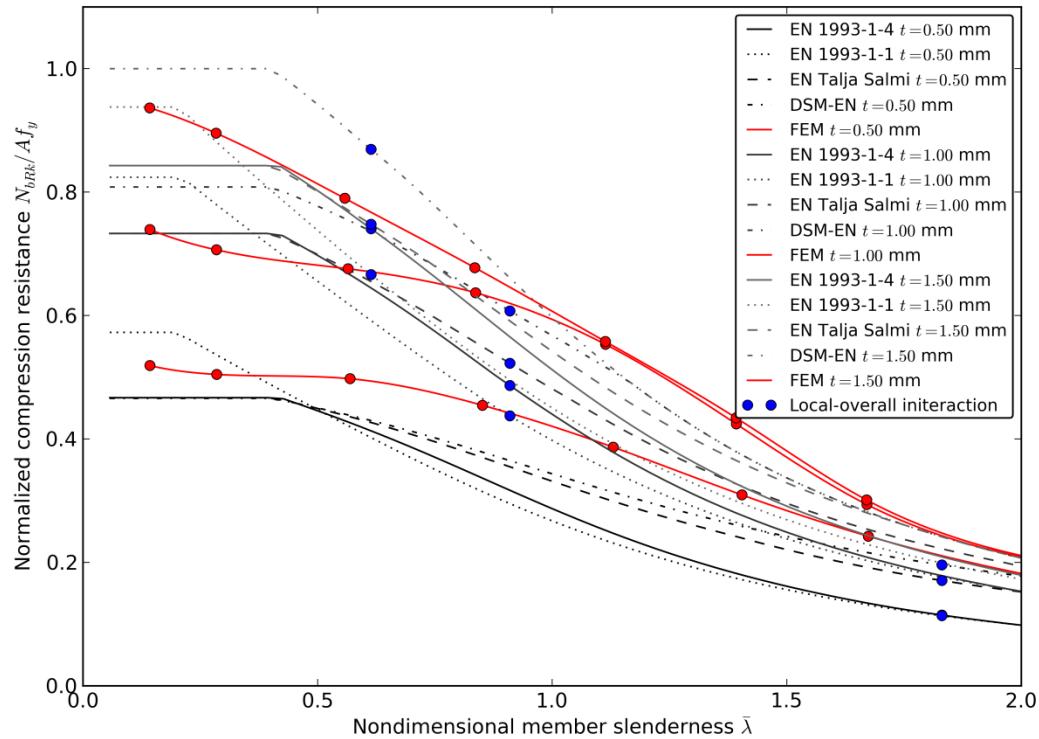


Figure 9. Nondimensional compression resistance of Section B with variable member slenderness.

(b) Columns with variable thickness and fixed length to 0.5, 0.75 and 1.0 m

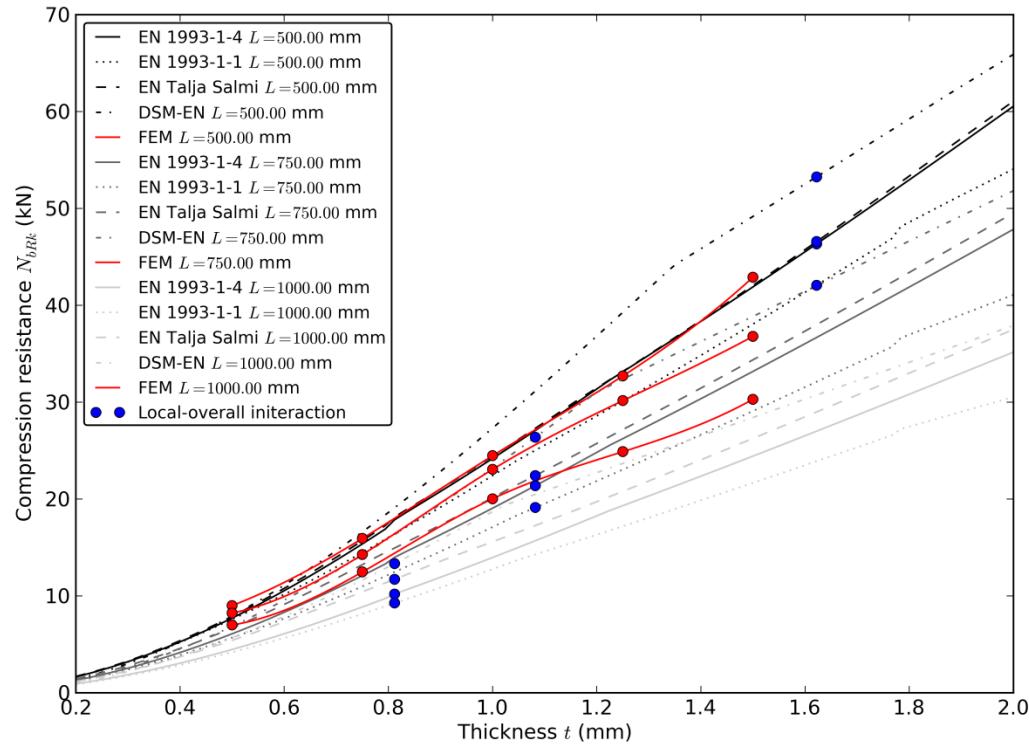


Figure 10. Compression resistance of Section B with variable thickness.

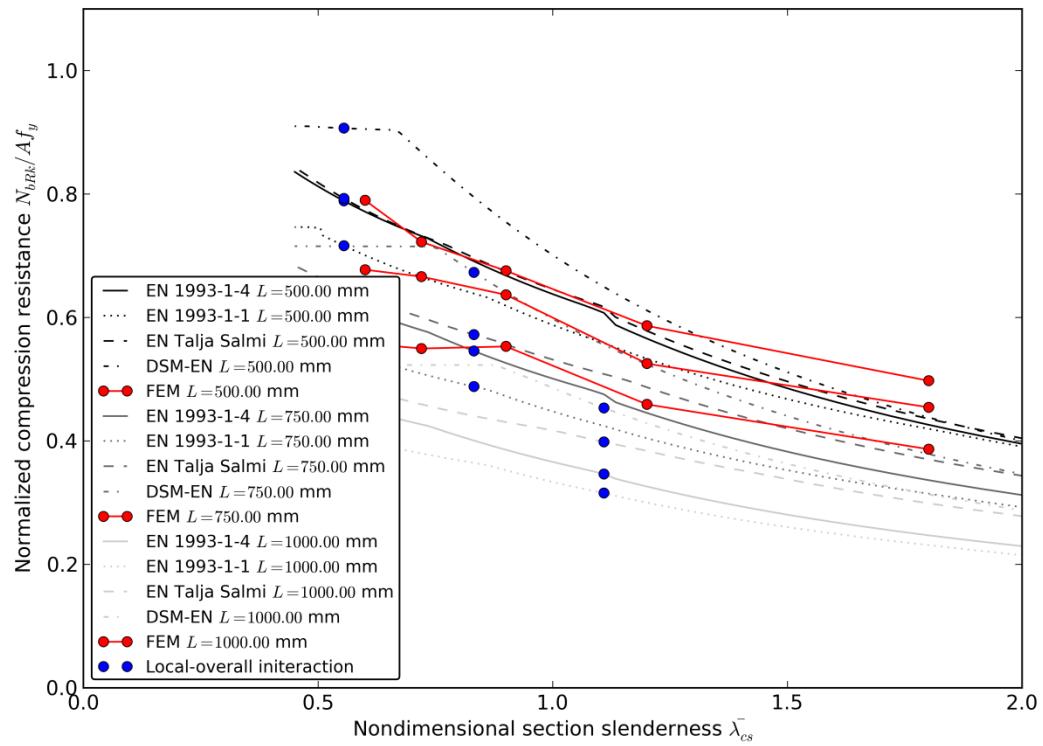


Figure 11. Nondimensional compression resistance of Section B with variable section slenderness.

(c) Comparison to FEM results

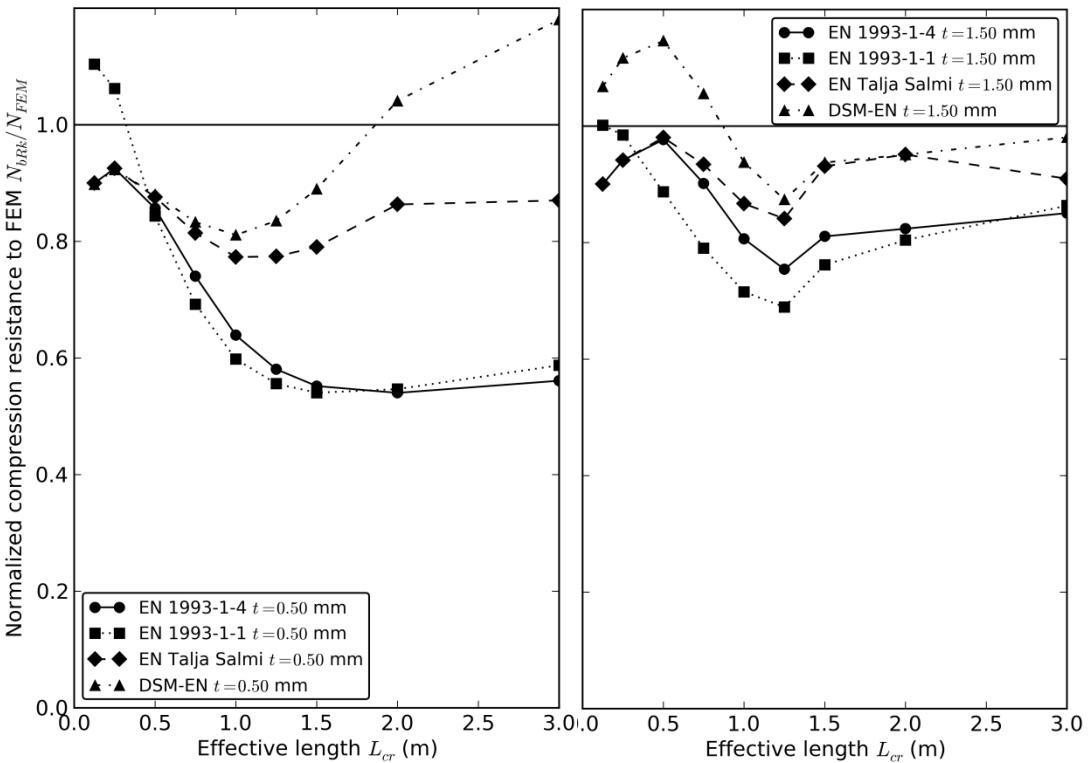


Figure 12. Compression resistance normalized to FEM results with respect to the variable length.

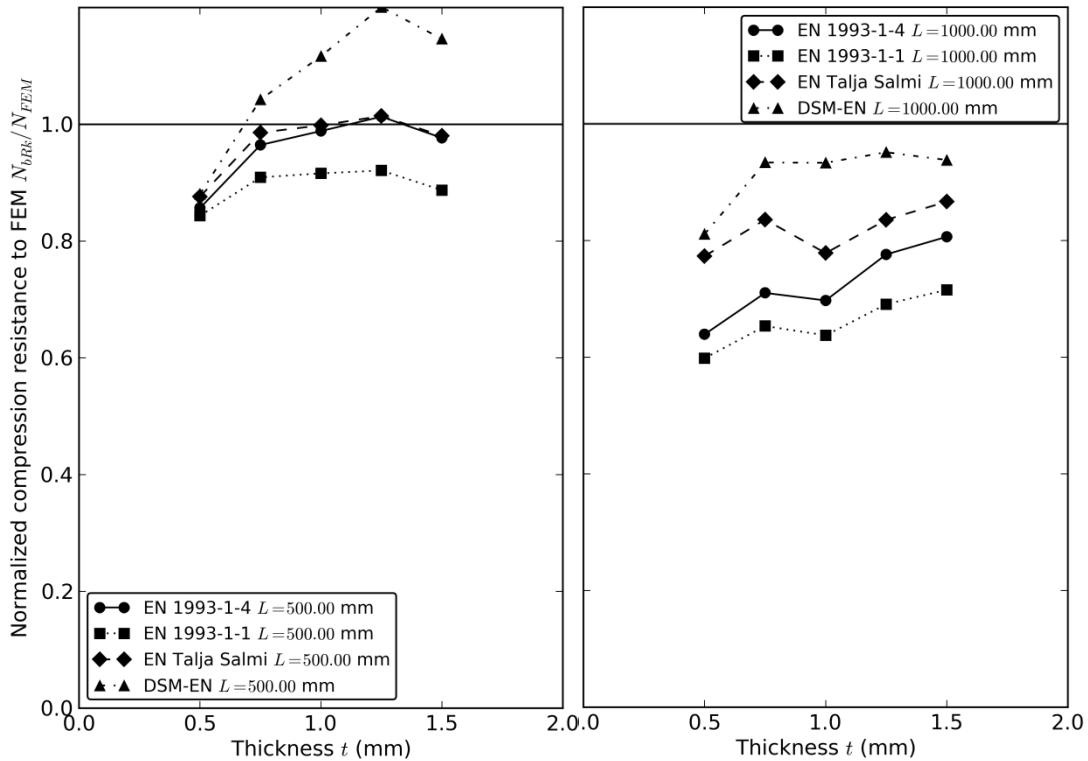


Figure 13. Compression resistance normalized to FEM results with respect to the variable thickness.

7 Discussion

Results show that the DSM method did not show significantly better results in comparison to the existing effective width method (see Figure 6 and Figure 12). However, both seem to be slightly over-predicting the member capacity in very short columns and tend to be more conservative with the increasing length (see Figure 7 and Figure 13). This effect can be caused by unnecessary reduction of sections that fail in overall buckling at low stress levels in the case of the effective section calculation. It was partly eliminated by applying the approach from AISI and AS/NZS standards recommended by Talja and Salmi. Smaller thicknesses are somewhat more conservative compared to the FEM results.

8 Conclusions

8.1 Effective Width Method

The plate slenderness calculation in EN 1993-1-4, Section 5.2.3 is based on stress equal to the material yield strength f_y . We recommend that the modification of the calculation should be considered, which takes into account the overall buckling stress of the full cross section (as it is used in AISI, ASCE and AS/NZS standards and as it is recommended by Talja and Salmi). The modified formula is presented in Eq. (24). The full cross-section shall be used in overall buckling calculation of the reduction factor χ .

$$\bar{\lambda}_p = \sqrt{\chi} \frac{\bar{b}/t}{28.4\epsilon k_\sigma}. \quad (24)$$

8.2 Direct Strength Method

The application of DSM in the member design does not provide significant improvement in the accuracy of results, but it is easier and more straightforward than the effective width and effective thickness calculations which usually need several iterations and are limited to simple cross-sections. The use of DSM is also limited to certain sectional shapes and loading combinations but its range can be extended by calibration without the need of more complex design rules.

DSM tends to be too conservative for sections with one part remarkably more slender than others (such as top hat sections with long unstiffened lips).

The main drawback of DSM use is the need of FSM or FEM software providing the accurate prediction of critical stress of local or distortional buckling. In that sense, a proper FEM analysis will produce much more accurate resistance prediction directly without the need of any further calculations.

Eurocode 3, Part 1-5 provides rules for calculation of local buckling elastic critical stress of plated elements, which can serve as a basis for manual calculation of cross-sectional local buckling critical stress. Moreover, the rules for distortional buckling critical stress of edge stiffeners are present in Eurocode 3, Part 1-3, and therefore the basic values of DSM are readily available in the code, so that the implementation of DSM method is possible. From the modified DSM rules recommended by Rossi and Rasmussen [16], only the distortional buckling calculation can be adapted into the Eurocode because the local and local-overall buckling resistances are related only to the AS/NZS rules in the presented form.

9 Recommendations

DSM stands between traditional design methods and more sophisticated numerical methods such as FEM, and it yields best results in its semi-numerical form, where critical stresses from FSM, FEM or other numerical simulations are used. Due to many limitations explained here or in the Design Guide [28], we do not recommend the method to be used in Eurocode since nowadays FEM calculations provide more realistic predictions with reasonable computational time. If the DSM is considered as appendix to EN 1993-1-4, the following issues should be taken into account:

- 1) Eurocode provides closed-form solutions of elastic buckling of plates (local buckling) and stiffeners (distortional buckling) that may be linked to the DSM.
- 2) If a numerical solution of elastic buckling is recommended, its algorithm should be reviewed. We recommend CUFSM, an open-source (Academic Free Licence) algorithm provided by Ben Schafer, which was used in this report.
- 3) Parameters of DSM curves have to be calibrated. The work by Becque et al. [10] provides one recommendation that may be used if it satisfies the reliability criteria.

- 4) The applicability of pre-qualified cross-section limits should be checked, because of the Eurocode specific rules for local and distortional critical stresses and overall buckling reduction factors.

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Appendix A: DSM limits for pre-qualified members

The geometrical and material limits in both standards (AISI S100:2007 and AS/NZS 4600:2005) are generally very similar, only small differences are highlighted in Table 7, Table 8, Table 9 and Table 10.

Table 7. Pre-qualified columns (Part 1/2).

Sections in compression	AISI S100 limits	AS/NZS 4600 limits
Lipped channels		
	$h_0/t < 472$ $b_0/t < 159$ $4 < D/t < 33$ $0,7 < h_0/b_0 < 5$ $0,05 < D/b_0 < 0,41$ $\theta = 90^\circ$ $E/f_y > 340 (f_y < 593 MPa)$	
Complex lips of lipped channels		
	$D_2/t < 34$ $D_2/D < 2$ $D_3/t < 34$ $D_3/D < 1$	not applicable
Lipped channels with web stiffener(s)		
	$h_0/t < 489$ $b_0/t < 160$ $6 < D/t < 33$ $1,3 < h_0/b_0 < 2,7$ $0,05 < D/b_0 < 0,41$ max. 2 stiffeners $E/f_y > 340 (f_y < 593 MPa)$	
Z-section		
	$h_0/t < 137$ $b_0/t < 56$ $0 < D/t < 36$ $1,5 < h_0/b_0 < 2,7$ $0 < D/b_0 < 0,73$ $\theta = 50^\circ$ $E/f_y > 590 (f_y < 345 MPa)$	

Table 8. Pre-qualified columns (Part 2/2).

Sections in compression	AISI S100 limits	AS/NZS 4600 limits
<p style="text-align: center;">Rack upright</p>	See Lipped channel with complex lips	$h_0/t < 51$ $b_0/t < 22$ $5 < D/t < 8$ $2,1 < h_0/b_0 < 2,9$ $1,6 < b_2/D < 2,0$ $D_2/h_0 = 0,3$ $\theta = 50^\circ$ $E/f_y > 340 \left(f_y < 593 \text{ MPa} \right)$
<p style="text-align: center;">Hat</p>		$h_0/t < 50$ $b_0/t < 20$ $4 < D/t < 6$ $1 < h_0/b_0 < 1,2$ $D/b_0 = 0,13$ $\theta = 50^\circ$ $E/f_y > 428 \left(f_y < 476 \text{ MPa} \right)$

Table 9. Pre-qualified beams (Part 1/2).

Sections in bending	AISI S100 limits	AS/NZS 4600 limits
<p>Hats (decks) with stiffened flange in compression</p>		$h_0/t < 97$ $b_0/t < 467$ $0 < b_t/t < 26$ $0,14 < h_0/b_0 < 0,87$ $0,88 < b_0/b_t < 5,4$ $E/f_y > 492 \left(f_y < 414 \text{ MPa} \right)$
<p>Trapezoids (decks) with stiff flange in compression</p>		$h_0/t < 203$ $b_0/t < 231$ $42 < (h_0/\sin \theta)/b_0 < 1,91$ $1,1 < h_0/b_t < 3,38$ max. 2 stiffeners per element $52^\circ < \theta < 84^\circ$ $E/f_y > 310 \left(f_y < 655 \text{ MPa} \right)$

Table 10. Pre-qualified beams (Part 2/2).

Sections in bending	AISI S100 limits	AS/NZS 4600 limits
Lipped channels 	$h_0/t < 321$ $b_0/t < 75$ $0 < D/t < 34$ $1,5 < h_0/b_0 < 17$ $0 < D/b_0 < 0,7$ $44^\circ < \theta < 90^\circ$ $E/f_y > 421 (f_y < 483 MPa)$	
Complex lips of lipped channels 	$D_2/t < 34$ $D_2/D < 2$ $D_3/t < 34$ $D_3/D < 1$	not applicable
Lipped channels with web stiffener(s) 	$h_0/t < 358$ $b_0/t < 58$ $14 < D/t < 17$ $5,5 < h_0/b_0 < 11,7$ $0,27 < D/b_0 < 0,56$ $\theta = 90^\circ$ $E/f_y > 578 (f_y < 352 MPa)$	
Z-section 	$h_0/t < 183$ $b_0/t < 71$ $10 < D/t < 16$ $2,5 < h_0/b_0 < 4,1$ $0,15 < D/b_0 < 0,34$ $36^\circ < \theta < 90^\circ$ $E/f_y > 440 (f_y < 462 MPa)$	$E/f_y > 400 (f_y < 462 MPa)$
Complex lips of Z-sections 	$D_2/t < 34$ $D_2/D < 2$ $D_3/t < 34$ $D_3/D < 1$	not applicable

Appendix B: Closed-form elastic buckling solutions

Local buckling

(a) element method

A conservative approach assumes that the critical elastic buckling load $\sigma_{cr,l}$ is the smallest buckling load of the cross-section plate elements $\sigma_{cr,el}$ (Eqs. (25) and (26)) with hinged corners. Alternatively, it can be calculated as the weighted average of plate critical loads which may result in higher prediction in some cases. The values t_{el} and b_{el} stand for the element thickness and width respectively. The factor k is usually 4 for intermediate and 0.425 for outstanding elements. This approach is discussed in more detail in Appendix C.

$$\sigma_{cr,l} = \min(\sigma_{cr,el}) \text{ or } \sigma_{cr,l} = \frac{\sum \sigma_{cr,el} b_{el}}{\sum b_{el}}. \quad (25)$$

$$\sigma_{cr,el} = k \frac{\pi^2 E}{12(1-\mu^2)} \left(\frac{t_{el}}{b_{el}} \right)^2. \quad (26)$$

(b) interaction method for lipped channels

More accurate prediction can be achieved by taking into account the interaction between section elements. Such methods are, however, restricted to the certain cross sections. In this example the flange-lip ($f-l$) and flange-web ($f-w$) interaction of lipped channel is calculated [3].

$$\sigma_{cr,l} = \min(\sigma_{cr,f-l}, \sigma_{cr,f-w}). \quad (27)$$

$$\begin{aligned} \sigma_{cr,f-l} &= k_{f-l} \frac{\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{b_0} \right)^2 \\ \sigma_{cr,f-w} &= k_{f-w} \frac{\pi^2 E}{12(1-\mu^2)} \left(\frac{t}{b_0} \right)^2. \end{aligned} \quad (28)$$

$$\begin{aligned} k_{f-l} &= -11,07 \left(\frac{D}{b_0} \right)^2 + 3,95 \left(\frac{D}{b_0} \right) + 4 \quad \left(\frac{D}{b_0} \right) < 0,6 \\ k_{f-w} &= \begin{cases} 4 \left[2 - \left(\frac{b_0}{h_0} \right)^{0,4} \right] \left(\frac{b_0}{h_0} \right)^2 & \text{when } \left(\frac{h_0}{b_0} \right) \geq 1 \\ 4 \left[2 - \left(\frac{h_0}{b_0} \right)^{0,2} \right] & \text{else} \end{cases}. \end{aligned} \quad (29)$$

Distortional buckling

The manual calculation of distortional buckling in Eurocode is based on isolation of edge stiffeners that consists of section flange and lip and then calculation of their sectional properties (A_s and I_s) and rotational spring stiffness K .

$$\sigma_{cr,s} = \frac{2\sqrt{KEI_s}}{A_s}. \quad (30)$$

Similar methods are implemented in EN 1993-1-5, AS/NZS and AISI standards. The calculation of critical load of lipped C and Z sections is developed in [3]. The results can be used for DSM application or for the stiffener thickness reduction as in EN 1993.

Overall buckling

For columns subjected to overall buckling, the critical stress is always the smallest of critical stresses of all possible overall failure modes. Depending on the cross-section shape, it could be flexural buckling to y or z axis $\sigma_{E,y(z)}$, torsional buckling σ_T or torsional-flexural buckling $\sigma_{TF,y(z)}$. The support conditions are taken into account by reducing or extending the critical length to y and z axis $L_{cr,y(z)}$ and in torsion $L_{cr,T}$.

$$\sigma_{E,y(z)} = \frac{\pi^2 E}{(L_{cr,y(z)}/i_{y(z)})^2}. \quad (31)$$

$$\sigma_T = \frac{1}{A_g i_0^2} \left(GI_t + \frac{\pi^2 EI_w}{L_{cr,T}^2} \right), \text{ where } i_0 = \sqrt{i_y^2 + i_z^2 + y_0^2 + z_0^2}. \quad (32)$$

$$\sigma_{TF,y(z)} = \frac{1}{2\beta_{y(z)}} \left[(\sigma_{E,y(z)} + \sigma_T)^2 - 4\beta_{y(z)}\sigma_{E,y(z)}\sigma_T \right], \text{ where} \\ \beta_y = 1 - (z_0/i_0)^2 \text{ and } \beta_z = 1 - (y_0/i_0)^2. \quad (33)$$

Appendix C: Example calculations of studied cross-sections

The following calculation protocols were automatically generated by Python script producing TeX document and converted to pdf format. The idea was to provide a simple tool that is able to produce calculation protocols of most of the current design methods that can be easily applied to any cold-formed cross-sections. The resistances of Section A and Section B are calculated with effective length 1.0 m and material thickness 1.0 mm.

Compressive strength of Section A
(Liped channel 72x36 mm)

Petr Hradil

March 28, 2013

Contents

1	Compression resistance according to EN 1993 rules for stainless steel	3
1.1	Cross-section classification	3
1.2	Gross cross-section	3
1.3	Effective cross-section	3
1.3.1	Upper lip	3
1.3.2	Upper flange	3
1.3.3	Web	4
1.3.4	Lower flange	4
1.3.5	Lower lip	4
1.3.6	The effect of edge stiffeners	4
1.3.7	Sectional properties	4
1.4	Member buckling resistance	5
2	Compression resistance according to EN 1993 rules for carbon steel	6
2.1	Cross-section classification	6
2.2	Gross cross-section	6
2.3	Effective cross-section	6
2.3.1	Upper lip	6
2.3.2	Web	6
2.3.3	Lower lip	7
2.3.4	The effect of edge stiffeners	7
2.3.5	Sectional properties	7
2.4	Member buckling resistance	7
3	Compression resistance according to EN 1993 rules for stainless steel modified by Talja and Salmi	9
3.1	Gross cross-section	9
3.2	Member buckling resistance	9
3.3	Cross-section classification	9
3.4	Effective cross-section	10
3.4.1	Upper lip	10
3.4.2	Upper flange	10
3.4.3	Web	10
3.4.4	Lower flange	10
3.4.5	Lower lip	10
3.4.6	The effect of edge stiffeners	10
3.4.7	Sectional properties	11
4	Compression resistance using DSM according to Becque et al. for EN 1993	12
4.1	Distortional buckling	12
4.2	Overall and local buckling interaction	12
5	Compression resistance using CSM	14
6	Effective sections reduction factors	14

1 Compression resistance according to EN 1993 rules for stainless steel

1.1 Cross-section classification

Upper lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Upper flanger: $c/t = 36/1.0 = 36.0 > 29.0$ Class 4
 Web: $c/t = 72/1.0 = 72.0 > 29.0$ Class 4
 Lower flange: $c/t = 36/1.0 = 36.0 > 29.0$ Class 4
 Lower lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Class 4 cross-section.

1.2 Gross cross-section

$$\begin{aligned} A_{\text{real}} &= 169 \text{ mm}^2 \\ A_{g,sh} &= \sum_{i=1}^m b_i t_i = 174 \text{ mm}^2 \\ I_{g,sh,x} &= 149352 \text{ mm}^4 \\ I_{g,sh,y} &= 37548 \text{ mm}^4 \\ &\quad \sum_{i=1}^n r_j \frac{t_j}{w} \\ \delta &= 0.43 \frac{\sum_{i=1}^{j-1} b_i t_i}{\sum_{i=1}^m b_i t_i} = 0.031 \text{ (EN 1993-1-3 (5.1))} \\ A_g &= A_{g,sh}(1 - \delta) = 174(1 - 0.031) = 169 \text{ mm}^2 \\ I_{g,x} &= I_{g,sh,x}(1 - 2\delta) = 149352(1 - 2 \cdot 0.031) = 140121 \text{ mm}^4 \\ I_{g,y} &= I_{g,sh,y}(1 - 2\delta) = 37548(1 - 2 \cdot 0.031) = 35227 \text{ mm}^4 \end{aligned}$$

1.3 Effective cross-section

$\chi_d = 0.936$ after 2 iterations

1.3.1 Upper lip

$$\begin{aligned} k_\sigma &= 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p &= \chi_d \frac{b/t}{28.4 \sqrt{k_\sigma}} = 0.936 \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.732 \\ \text{for outstanding element } \rho &= \frac{1.0}{\bar{\lambda}_p} - \frac{0.231}{\bar{\lambda}_p^2} = \frac{1.0}{0.73} - \frac{0.231}{0.73^2} = 0.935 \text{ (EN 1993-1-4)} \end{aligned}$$

1.3.2 Upper flange

$$\begin{aligned} k_\sigma &= 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p &= \chi_d \frac{b/t}{28.4 \sqrt{k_\sigma}} = 0.936 \frac{34/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 0.582 \\ \text{for internal element } \rho &= \frac{0.722}{\bar{\lambda}_p} - \frac{0.125}{\bar{\lambda}_p^2} = \frac{0.722}{0.58} - \frac{0.125}{0.58^2} = 0.871 \text{ (EN 1993-1-4)} \end{aligned}$$



Figure 1: Effective section of Lipped channel 36.0x72.0x15.0 1.0 mm

$$\begin{aligned}
 N_{er,T} &= \frac{1}{I_0}(GI_t + \frac{\pi^2 EI_{xx}}{L_{cr,x}^2}) = \frac{1}{49.4757}(76923 \cdot 56 + \frac{\pi^2 200000 \cdot 51567855}{1000^2}) = 43.4 \text{ kN} \\
 \beta &= 1 - (\frac{s_0}{r_0})^2 = 0.539 \\
 N_{er,TF} &= \frac{1}{2\beta}[N_{er,T} + N_{er,x} - \sqrt{(N_{er,T} + N_{er,x})^2 - 4\beta N_{er,T} N_{er,x}}] = 39.9 \text{ kN} \\
 N_{er} &= \min(N_{er,TF}, N_{er,y}) = 39.9 \text{ kN (singly symmetric section)} \\
 \bar{\lambda} &= \sqrt{\frac{A_f I_x}{N_{er}}} = \sqrt{\frac{119.250}{39930.2}} = 0.862 \\
 \phi &= \frac{1}{2}(1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2) = \frac{1}{2}(1 + 0.49(0.86 - 0.4) + 0.86^2) = 0.985 \\
 \chi &= \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} = \frac{1}{0.98 + \sqrt{0.98^2 - 0.86^2}} \leq 1 \quad \chi = 0.685 \\
 N_{b,Rk} &= \chi A f_y = 0.68 \cdot 119 \cdot 250 = 20.3 \text{ kN}
 \end{aligned}$$

2 Compression resistance according to EN 1993 rules for carbon steel

2.1 Cross-section classification

Upper lip: $c/t = 15/1.0 = 15.0 > 13.6$ Class 4
 Upper flange: $c/t = 36/1.0 = 36.0 \leq 40.7$ Class 3
 Web: $c/t = 72/1.0 = 72.0 > 40.7$ Class 4
 Lower flange: $c/t = 36/1.0 = 36.0 \leq 40.7$ Class 3
 Lower lip: $c/t = 15/1.0 = 15.0 > 13.6$ Class 4
 Class 4 cross-section.

2.2 Gross cross-section

$$\begin{aligned} A_{real} &= 169 \text{ mm}^2 \\ A_{g,sh} &= \sum_{i=1}^m b_i t_i = 174 \text{ mm}^2 \\ I_{g,sh,x} &= 149352 \text{ mm}^4 \\ I_{g,sh,y} &= 37548 \text{ mm}^4 \\ \delta &= 0.43 \frac{\sum_{i=1}^{j-1} r_j \frac{b_j}{t_j}}{\sum_{i=1}^m b_{p,i}} = 0.031 \text{ (EN 1993-1-3 (5.1))} \\ A_g &= A_{g,sh}(1 - \delta) = 174(1 - 0.031) = 169 \text{ mm}^2 \\ I_{g,x} &= I_{g,sh,x}(1 - 2\delta) = 149352(1 - 2 \cdot 0.031) = 140121 \text{ mm}^4 \\ I_{g,y} &= I_{g,sh,y}(1 - 2\delta) = 37548(1 - 2 \cdot 0.031) = 35227 \text{ mm}^4 \end{aligned}$$

2.3 Effective cross-section

$\chi_d = 0.944$ after 2 iterations

2.3.1 Upper lip

$$\begin{aligned} k_\sigma &= 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p &= \chi_d \frac{b/t}{28.4c\sqrt{k_\sigma}} = 0.944 \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.738 \\ \text{for outstanding element and } \bar{\lambda}_p &\leq 0.748 \rho = 1 \text{ (EN 1993-1-5 (4.3))} \end{aligned}$$

2.3.2 Web

$$\begin{aligned} k_\sigma &= 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p &= \frac{b/t}{28.4c\sqrt{k_\sigma}} = \frac{70/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 1.276 \\ \text{for internal element and } \bar{\lambda}_p &> 0.673 \\ \rho &= \frac{\bar{\lambda}_p - 0.055(3+\psi)}{\bar{\lambda}_p^2} = \frac{1.28 - 0.055(3+1.0)}{1.28^2} = 0.649 \text{ (EN 1993-1-5 (4.2))} \end{aligned}$$

2.3.3 Lower lip

$$k_\sigma = 0.430 \text{ (EN 1993-1-5, Table 4.2)}$$

$$\bar{\lambda}_p = \chi_d \frac{b/t}{28.4\sqrt{k_\sigma}} = 0.944 \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.738$$

for outstanding element and $\lambda_p \leq 0.748$ $\rho = 1$ (EN 1993-1-5 (4.3))

2.3.4 The effect of edge stiffeners

$$\sigma_{com,Ed} = f_y = 250.000 \text{ MPa}$$

$$k_f = \frac{A_{s2}}{A_{s1}} = \frac{33.0}{33.0} = 1.000$$

$$K = \frac{EI^3}{4(1-\nu^2)} \cdot \frac{1}{b_1^2 h_w + b_1^2 + 0.5b_1 b_2 h_w k_f} = \frac{200000 \cdot 1.0^3}{4(1-0.3^2)} \cdot \frac{1}{31^2 \cdot 72 + 31^2 + 0.5 \cdot 31 \cdot 31 \cdot 72 \cdot 1} = 0.41$$

$$\sigma_{cr,s} = \frac{2\sqrt{KEI_s}}{A_s} = \frac{2\sqrt{0.4 \cdot 200000 \cdot 743}}{33.0} = 472.3 \text{ MPa}$$

$$\bar{\lambda}_d = \sqrt{\frac{f_y}{\sigma_{cr,s}}} = \sqrt{\frac{250.0}{472.3}} = 0.728$$

$$\chi_d = 1.47 - 0.723 \bar{\lambda}_d = 1.47 - 0.723 \cdot 0.7 = 0.944 \text{ for } \bar{\lambda}_d \leq 1.38$$

$$A_{s,red} = \chi_d A_s = 0.944 \cdot 33.0 = 28.3 \text{ mm}^2$$

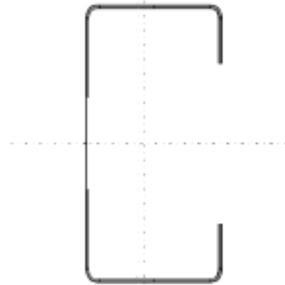


Figure 2: Effective section of Lipped channel 36.0x72.0x15.0 1.0 mm

2.3.5 Sectional properties

$$A_{eff} = 141 \text{ mm}^2$$

$$I_{x,eff} = 144089 \text{ mm}^4$$

$$I_{y,eff} = 31183 \text{ mm}^4$$

$$e_x = 1.87 \text{ mm}$$

2.4 Member buckling resistance

Buckling curve d, $\alpha = 0.76$, $\bar{\lambda}_0 = 0.2 i_0 = \sqrt{i_x^2 + i_y^2 + x_0^2} = \sqrt{32.0^2 + 14.9^2 + 33.6^2} = 48.7 \text{ mm}$

$$\begin{aligned}
 N_{cr,x} &= \frac{\pi^2 EI_x}{L_{cr,x}^2} = \frac{\pi^2 200000-144089}{1000^2} = 284.4 \text{ kN} \\
 N_{cr,y} &= \frac{\pi^2 EI_y}{L_{cr,y}^2} = \frac{\pi^2 200000-31183}{1000^2} = 61.6 \text{ kN} \\
 N_{cr,T} &= \frac{1}{\ell_0} (GI_t + \frac{\pi^2 EI_w}{L_{cr,T}^2}) = \frac{1}{48.734^2} (76923 \cdot 56 + \frac{\pi^2 200000-51567855}{1000^2}) = 44.7 \text{ kN} \\
 \beta &= 1 - (\frac{x_0}{r_0})^2 = 0.525 \\
 N_{cr,TF} &= \frac{1}{2\beta} [N_{cr,T} + N_{cr,x} - \sqrt{(N_{cr,T} + N_{cr,x})^2 - 4\beta N_{cr,T} N_{cr,x}}] = 41.3 \text{ kN} \\
 N_{cr} &= \min(N_{cr,TF}, N_{cr,y}) = 41.3 \text{ kN (singly symmetric section)} \\
 \bar{\lambda} &= \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{141.250}{41338.2}} = 0.922 \\
 \phi &= \frac{1}{2}(1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2) = \frac{1}{2}(1 + 0.76(0.92 - 0.2) + 0.92^2) = 1.200 \\
 \chi &= \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} = \frac{1}{1.20 + \sqrt{1.20^2 - 0.92^2}} \leq 1 \quad \chi = 0.508 \\
 N_{b,Rk} &= \chi A f_y = 0.51 \cdot 141 \cdot 250 = 17.9 \text{ kN}
 \end{aligned}$$

3 Compression resistance according to EN 1993 rules for stainless steel modified by Talja and Salmi

3.1 Gross cross-section

$$\begin{aligned}
 A_{real} &= 169 \text{ mm}^2 \\
 A_{g,sh} &= \sum_{i=1}^m b_i t_i = 174 \text{ mm}^2 \\
 I_{g,sh,x} &= 149352 \text{ mm}^4 \\
 I_{g,sh,y} &= 37548 \text{ mm}^4 \\
 \delta &= 0.43 \frac{\sum_{i=1}^{j-1} r_j \frac{t_i}{100}}{\sum_{i=1}^n b_{p,i}} = 0.031 \text{ (EN 1993-1-3 (5.1))} \\
 A_g &= A_{g,sh}(1 - \delta) = 174(1 - 0.031) = 169 \text{ mm}^2 \\
 I_{g,x} &= I_{g,sh,x}(1 - 2\delta) = 149352(1 - 2 \cdot 0.031) = 140121 \text{ mm}^4 \\
 I_{g,y} &= I_{g,sh,y}(1 - 2\delta) = 37548(1 - 2 \cdot 0.031) = 35227 \text{ mm}^4
 \end{aligned}$$

3.2 Member buckling resistance

$$\begin{aligned}
 \alpha &= 0.49, \bar{\lambda}_0 = 0.4 \\
 i_0 &= \sqrt{i_x^2 + i_y^2 + x_0^2} = \sqrt{29.7^2 + 14.9^2 + 33.6^2} = 47.3 \text{ mm} \\
 N_{cr,x} &= \frac{\pi^2 EI_x}{L_{cr,x}^2} = \frac{\pi^2 200000 \cdot 149352}{1000^2} = 294.8 \text{ kN} \\
 N_{cr,y} &= \frac{\pi^2 EI_y}{L_{cr,y}^2} = \frac{\pi^2 200000 \cdot 37548}{1000^2} = 74.1 \text{ kN} \\
 N_{cr,T} &= \frac{1}{i_0^2} (GI_t + \frac{\pi^2 EI_w}{L_{cr,y}^2}) = \frac{1}{47.38^2} (76923 \cdot 56 + \frac{\pi^2 200000 \cdot 51567855}{1000^2}) = 47.5 \text{ kN} \\
 \beta &= 1 - (\frac{x_0}{r_0})^2 = 0.495 \\
 N_{er,TF} &= \frac{1}{2\beta} [N_{er,T} + N_{er,x} - \sqrt{(N_{er,T} + N_{er,x})^2 - 4\beta N_{er,T} N_{er,x}}] = 43.6 \text{ kN} \\
 N_{er} &= \min(N_{er,TF}, N_{er,y}) = 43.6 \text{ kN (singly symmetric section)} \\
 \bar{\lambda} &= \sqrt{\frac{A_f y}{N_{er}}} = \sqrt{\frac{169 \cdot 250}{43638.7}} = 0.984 \\
 \phi &= \frac{1}{2} (1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2) = \frac{1}{2} (1 + 0.49(0.98 - 0.4) + 0.98^2) = 1.127 \\
 \chi &= \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} = \frac{1}{1.127 + \sqrt{1.127^2 - 0.98^2}} \leq 1 \quad \chi = 0.597
 \end{aligned}$$

3.3 Cross-section classification

Upper lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Upper flange: $c/t = 36/1.0 = 36.0 > 29.0$ Class 4
 Web: $c/t = 72/1.0 = 72.0 > 29.0$ Class 4
 Lower flange: $c/t = 36/1.0 = 36.0 > 29.0$ Class 4
 Lower lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Class 4 cross-section.

3.4 Effective cross-section

$\chi_d = 0.945$ after 4 iterations

3.4.1 Upper lip

$$k_\sigma = 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p = \chi_d \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = 0.945 \sqrt{0.597} \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.571 \\ \text{for outstanding element } \rho = 1 \text{ (EN 1993-1-4)}$$

3.4.2 Upper flange

$$k_\sigma = 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p = \chi_d \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = 0.945 \sqrt{0.597} \frac{34/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 0.454 \\ \text{for internal element } \rho = \frac{0.722}{\bar{\lambda}_p^2} - \frac{0.125}{\bar{\lambda}_p^2} = \frac{0.722}{0.45^2} - \frac{0.125}{0.45^2} = 0.984 \text{ (EN 1993-1-4)}$$

3.4.3 Web

$$k_\sigma = 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p = \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = \sqrt{0.597} \frac{70/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 0.985 \\ \text{for internal element } \rho = \frac{0.722}{\bar{\lambda}_p^2} - \frac{0.125}{\bar{\lambda}_p^2} = \frac{0.722}{0.99^2} - \frac{0.125}{0.99^2} = 0.604 \text{ (EN 1993-1-4)}$$

3.4.4 Lower flange

$$k_\sigma = 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p = \chi_d \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = 0.945 \sqrt{0.597} \frac{34/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 0.454 \\ \text{for internal element } \rho = \frac{0.722}{\bar{\lambda}_p^2} - \frac{0.125}{\bar{\lambda}_p^2} = \frac{0.722}{0.45^2} - \frac{0.125}{0.45^2} = 0.984 \text{ (EN 1993-1-4)}$$

3.4.5 Lower lip

$$k_\sigma = 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p = \chi_d \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = 0.945 \sqrt{0.597} \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.571 \\ \text{for outstanding element } \rho = 1 \text{ (EN 1993-1-4)}$$

3.4.6 The effect of edge stiffeners

$$\sigma_{com,Ed} = f_y = 250.000 \text{ MPa} \\ k_f = \frac{A_{st}}{A_{st}^2} = \frac{32.7}{32.7} = 1.000 \\ K = \frac{E t^3}{4(1-\nu^2)} \cdot \frac{1}{b_1^2 h_w + b_1^2 + 0.5 b_1 b_2 h_w k_f} = \frac{200000 \cdot 1.0^3}{4(1-0.3^2)} \cdot \frac{1}{31^2 \cdot 72 + 31^2 + 0.5 \cdot 31 \cdot 31 \cdot 72 \cdot 1} = 0.41 \\ \sigma_{er,s} = \frac{2\sqrt{K E I_s}}{A_s} = \frac{2\sqrt{0.4 \cdot 200000 \cdot 740}}{32.7} = 473.4 \text{ MPa} \\ \bar{\lambda}_d = \sqrt{\frac{f_y}{\sigma_{er,s}}} = \sqrt{\frac{250.0}{473.4}} = 0.727 \\ \chi_d = 1.47 - 0.723 \bar{\lambda}_d = 1.47 - 0.723 \cdot 0.7 = 0.945 \text{ for } \bar{\lambda}_d \leq 1.38 \\ A_{s,red1} = \chi_d A_{s1} = 0.945 \cdot 32.7 = 28.1 \text{ mm}^2$$

$$A_{s,\text{red2}} = \chi_{d1} A_{s2} = 0.945 \cdot 32.7 = 28.1 \text{ mm}^2$$

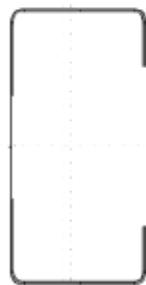


Figure 3: Effective section of Lipped channel 36.0x72.0x15.0 1.0 mm

3.4.7 Sectional properties

$$\begin{aligned}A_{eff} &= 136 \text{ mm}^2 \\I_{x,eff} &= 142221 \text{ mm}^4 \\I_{y,eff} &= 30414 \text{ mm}^4 \\c_x &= 2.20 \text{ mm} \\N_{b,Rk} &= \chi A f_y = 0.60 \cdot 136 \cdot 250 = 20.4 \text{ kN}\end{aligned}$$

4 Compression resistance using DSM according to Becque et al. for EN 1993

$$\begin{aligned}
 A_{real} &= 169 \text{ mm}^2 \\
 A_{g,sh} &= \sum_{i=1}^m b_i t_i = 174 \text{ mm}^2 \\
 I_{g,sh,x} &= 149352 \text{ mm}^2 \\
 I_{g,sh,y} &= 37548 \text{ mm}^2 \\
 \delta &= 0.43 \frac{\sum_{i=1}^m \frac{t_i}{b_i}}{\sum_{i=1}^n b_{p,i}} = 0.031 \text{ (EN 1993-1-3 (5.1))} \\
 A_g &= A_{g,sh}(1 - \delta) = 174(1 - 0.031) = 169 \text{ mm}^2 \\
 I_{g,x} &= I_{g,sh,x}(1 - 2\delta) = 149352(1 - 2 \cdot 0.031) = 140121 \text{ mm}^4 \\
 I_{g,y} &= I_{g,sh,y}(1 - 2\delta) = 37548(1 - 2 \cdot 0.031) = 35227 \text{ mm}^4
 \end{aligned}$$

4.1 Distortional buckling

$$\begin{aligned}
 k_f &= \frac{A_{sx}}{A_{s1}} = \frac{61.0}{61.0} = 1.000 \\
 K &= \frac{EI_x}{4(1-\nu^2)} \cdot \frac{1}{b_1^2 h_w + b_1^3 + 0.5 b_1 b_2 h_w k_f} = \frac{200000 \cdot 1.0^3}{4(1-0.3^2)} \cdot \frac{1}{23^2 \cdot 72 + 23^3 + 0.5 \cdot 23 \cdot 23 \cdot 72 \cdot 1} = 0.77 \\
 \sigma_{cr,s} &= \frac{2\sqrt{K EI_x}}{A_s} = \frac{2\sqrt{0.8 \cdot 200000 \cdot 880}}{61.0} = 456.8 \text{ MPa} \\
 \lambda &= \sqrt{\frac{f_y}{\sigma_{cr}}} = \sqrt{\frac{250}{457}} = 0.740 \\
 f_{y,red} &= \left(\frac{0.90}{0.74^{1.00}} - \frac{0.20}{0.74^{2.00}} \right) f_y = 216 \text{ MPa for } \lambda > 0.533 \\
 N_b &= f_{y,red} A = 216 \cdot 169 = 36.5 \text{ kN}
 \end{aligned}$$

4.2 Overall and local buckling interaction

$$\begin{aligned}
 \sigma_{cr} &= k \frac{\pi^2 E}{12(1-\nu)^2} \left(\frac{L}{b} \right)^2 = 4.0 \frac{\pi^2 200000}{12(1-0.3)^2} \left(\frac{1.0}{66} \right)^2 = 308 \text{ MPa} \\
 (\text{for Web}) \alpha &= 0.49, \bar{\lambda}_0 = 0.4 \\
 i_0 &= \sqrt{i_x^2 + i_y^2 + x_0^2} = \sqrt{29.7^2 + 14.9^2 + 33.6^2} = 47.3 \text{ mm} \\
 N_{er,x} &= \frac{\pi^2 EI_x}{L_{er,x}^2} = \frac{\pi^2 200000 \cdot 149352}{1000^2} = 294.8 \text{ kN} \\
 N_{er,y} &= \frac{\pi^2 EI_y}{L_{er,y}^2} = \frac{\pi^2 200000 \cdot 37548}{1000^2} = 74.1 \text{ kN} \\
 N_{er,T} &= \frac{1}{i_0} \left(GI_t + \frac{\pi^2 EI_x}{L_{er,x}^2} \right) = \frac{1}{47.3^2} (76923 \cdot 56 + \frac{\pi^2 200000 \cdot 51567855}{1000^2}) = 47.5 \text{ kN} \\
 \beta &= 1 - \left(\frac{x_0}{r_0} \right)^2 = 0.495 \\
 N_{er,TF} &= \frac{1}{2\beta} [N_{er,T} + N_{er,x} - \sqrt{(N_{er,T} + N_{er,x})^2 - 4\beta N_{er,T} N_{er,x}}] = 43.6 \text{ kN} \\
 N_{er} &= \min(N_{er,TF}, N_{er,y}) = 43.6 \text{ kN (singly symmetric section)} \\
 \bar{\lambda} &= \sqrt{\frac{f_y}{N_{er}}} = \sqrt{\frac{169-250}{43638.7}} = 0.984 \\
 \phi &= \frac{1}{2} (1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2) = \frac{1}{2} (1 + 0.49(0.98 - 0.4) + 0.98^2) = 1.127 \\
 \chi &= \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} = \frac{1}{1.13 + \sqrt{1.13^2 - 0.98^2}} \leq 1 \quad \chi = 0.597 \\
 \lambda &= \sqrt{\frac{f_y}{\sigma_{cr}}} = \sqrt{\frac{0.597-250}{308}} = 0.696 \\
 f_{y,red} &= \left(\frac{0.90}{0.70^{1.00}} - \frac{0.20}{0.70^{2.00}} \right) f_y = 238 \text{ MPa for } \lambda > 0.550
 \end{aligned}$$

$$N_b = \chi f_{y,red} A = 0.597 \cdot 238 \cdot 169 = 24.0 kN$$

5 Compression resistance using CSM

$$\sigma_{cr} = k \frac{\pi^2 E}{12(1-\nu)^2} \left(\frac{l}{b}\right)^2 = 4.0 \frac{\pi^2 200000}{12(1-0.3)^2} \left(\frac{1.0}{66}\right)^2 = 308 \text{ MPa}$$

$$\lambda_p = \sqrt{\frac{k_e}{\sigma_{cr}}} = \sqrt{\frac{250}{308}} = 0.901$$

$\lambda_{cs} = \max(\lambda_p) = 0.901$ for Web

$$\frac{e_{cam}}{e_y} = \frac{0.25}{0.901 \cdot 0.8} = \frac{0.25}{0.901} = 0.365 \leq (15, \frac{0.1e_u}{e_y} = \frac{0.1 \cdot 0.286}{0.001})$$

$$f_{cam} = f_y + E_{sh} \epsilon_y (\frac{e_{cam}}{e_y} - 1) = 250 + 2355 \cdot 0.001(0.365 - 1) = 248.129 \text{ MPa}$$

$$N_{cam,Rk} = f_{cam} A = 250 \cdot 169 = 41.897 \text{ kN}$$

6 Effective sections reduction factors

EN 1993-1-4 width reduction

	0.5 mm	1.0 mm	1.5 mm
Web	0.264	0.489	0.676
Upper lip	0.734	0.935	1.000
Upper flange	0.678	0.871	1.000
Lower flange	0.678	0.871	1.000
Lower lip	0.734	0.935	1.000

EN 1993-1-4 thickness reduction

	0.5 mm	1.0 mm	1.5 mm
Upper lip	0.682	0.936	1.000
Upper flange	0.682	0.936	1.000
Lower flange	0.682	0.936	1.000
Lower lip	0.682	0.936	1.000

EN 1993-1-1 width reduction

	0.5 mm	1.0 mm	1.5 mm
Web	0.358	0.649	0.872
Upper lip	0.765	1.000	1.000
Upper flange	0.867	1.000	1.000
Lower flange	0.867	1.000	1.000
Lower lip	0.765	1.000	1.000

EN 1993-1-1 thickness reduction

	0.5 mm	1.0 mm	1.5 mm
Upper lip	0.690	0.944	1.000
Upper flange	0.690	0.944	1.000
Lower flange	0.690	0.944	1.000
Lower lip	0.690	0.944	1.000

Compressive strength of Section B
(Lipped channel 24x72 mm)

Petr Hradil

March 28, 2013

Contents

1	Compression resistance according to EN 1993 rules for stainless steel	4
1.1	Cross-section classification	4
1.2	Gross cross-section	4
1.3	Effective cross-section	4
1.3.1	Upper lip	4
1.3.2	Web	4
1.3.3	Lower lip	5
1.3.4	The effect of edge stiffeners	5
1.3.5	Sectional properties	5
1.4	Member buckling resistance	5
2	Compression resistance according to EN 1993 rules for carbon steel	7
2.1	Cross-section classification	7
2.2	Gross cross-section	7
2.3	Effective cross-section	7
2.3.1	Upper lip	7
2.3.2	Web	7
2.3.3	Lower lip	8
2.3.4	The effect of edge stiffeners	8
2.3.5	Sectional properties	8
2.4	Member buckling resistance	8
3	Compression resistance according to EN 1993 rules for stainless steel modified by Talja and Salmi	10
3.1	Gross cross-section	10
3.2	Member buckling resistance	10
3.3	Cross-section classification	10
3.4	Effective cross-section	11
3.4.1	Upper lip	11
3.4.2	Web	11
3.4.3	Lower lip	11
3.4.4	The effect of edge stiffeners	11
3.4.5	Sectional properties	11
4	Compression resistance using DSM according to Becque et al. for EN 1993	13
4.1	Distortional buckling	13
4.2	Overall and local buckling interaction	13
5	Compression resistance using CSM	15
6	Effective sections reduction factors	15

1 Compression resistance according to EN 1993 rules for stainless steel

1.1 Cross-section classification

Upper lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Upper flange: $c/t = 24/1.0 = 24.0 \leq 29.0$ Class 3
 Web: $c/t = 72/1.0 = 72.0 > 29.0$ Class 4
 Lower flange: $c/t = 24/1.0 = 24.0 \leq 29.0$ Class 3
 Lower lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Class 4 cross-section.

1.2 Gross cross-section

$$\begin{aligned} A_{real} &= 145 \text{ mm}^2 \\ A_{g,sh} &= \sum_{i=1}^m b_i t_i = 150 \text{ mm}^2 \\ I_{g,sh,x} &= 118246 \text{ mm}^4 \\ I_{g,sh,y} &= 15307 \text{ mm}^4 \\ \delta &= 0.43 \frac{\sum_{i=1}^{l-1} r_j \frac{t_i}{\sqrt{b_j}}}{\sum_{i=1}^m b_{p,i}} = 0.036 \text{ (EN 1993-1-3 (5.1))} \\ A_g &= A_{g,sh}(1 - \delta) = 150(1 - 0.036) = 145 \text{ mm}^2 \\ I_{g,x} &= I_{g,sh,x}(1 - 2\delta) = 118246(1 - 2 \cdot 0.036) = 109711 \text{ mm}^4 \\ I_{g,y} &= I_{g,sh,y}(1 - 2\delta) = 15307(1 - 2 \cdot 0.036) = 14202 \text{ mm}^4 \end{aligned}$$

1.3 Effective cross-section

$\chi_d = 1.000$ after 1 iterations

1.3.1 Upper lip

$$\begin{aligned} k_\sigma &= 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p &= \frac{b/t}{28.4c\sqrt{k_\sigma}} = \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.782 \\ \text{for outstanding element } \rho &= \frac{1.0}{\lambda_p} - \frac{0.231}{\lambda_p^2} = \frac{1.0}{0.78} - \frac{0.231}{0.78^2} = 0.901 \text{ (EN 1993-1-4)} \end{aligned}$$

1.3.2 Web

$$\begin{aligned} k_\sigma &= 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p &= \frac{b/t}{28.4c\sqrt{k_\sigma}} = \frac{70/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 1.276 \\ \text{for internal element } \rho &= \frac{0.722}{\lambda_p} - \frac{0.125}{\lambda_p^2} = \frac{0.722}{1.276} - \frac{0.125}{1.276^2} = 0.489 \text{ (EN 1993-1-4)} \end{aligned}$$

1.3.3 Lower lip

$k_\sigma = 0.430$ (EN 1993-1-5, Table 4.2)

$$\bar{\lambda}_p = \frac{b/t}{28.4t/\sqrt{k_\sigma}} = \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.782$$

$$\text{for outstanding element } \rho = \frac{1.0}{\lambda_p} - \frac{0.231}{\lambda_p^2} = \frac{1.0}{0.782} - \frac{0.231}{0.782^2} = 0.901 \text{ (EN 1993-1-4)}$$

1.3.4 The effect of edge stiffeners

$$\sigma_{com,Ed} = f_y = 250.000 \text{ MPa}$$

$$k_f = \frac{A_{st}}{A_{st}} = \frac{25.6}{25.6} = 1.000$$

$$K = \frac{E t^3}{4(1-\nu^2) \cdot b_1^2 h_w + b_1^2 + 0.5 b_1 b_2 h_w k_f} = \frac{200000 \cdot 1.0^3}{4(1-0.3^2)} \cdot \frac{1}{21^2 \cdot 72 + 21^2 + 0.5 \cdot 21 \cdot 21 \cdot 72 \cdot 1} = 0.95$$

$$\sigma_{cr,s} = \frac{2\sqrt{K EI_s}}{A_s} = \frac{2\sqrt{0.9 \cdot 200000 \cdot 506}}{25.6} = 764.6 \text{ MPa}$$

$$\bar{\lambda}_d = \sqrt{\frac{I_u}{\sigma_{cr,s}}} = \sqrt{\frac{260.0}{764.6}} = 0.572$$

$$\chi_d = 1.0 \text{ for } \bar{\lambda}_d \leq 0.65$$

$$A_{s,red} = \chi_d A_s = 1.000 \cdot 25.6 = 23.3 \text{ mm}^2$$

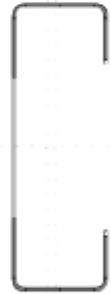


Figure 1: Effective section of Lipped channel 24.0x72.0x15.0 1.0 mm

1.3.5 Sectional properties

$$A_{eff} = 106 \text{ mm}^2$$

$$I_{x,eff} = 113080 \text{ mm}^4$$

$$I_{y,eff} = 11325 \text{ mm}^4$$

$$e_x = 2.40 \text{ mm}$$

1.4 Member buckling resistance

$$\alpha = 0.49, \bar{\lambda}_0 = 0.4$$

$$i_0 = \sqrt{i_x^2 + i_y^2 + x_0^2} = \sqrt{32.6^2 + 10.3^2 + 22.3^2} = 40.8 \text{ mm}$$

$$\begin{aligned}
 N_{er,x} &= \frac{\pi^2 EI_x}{L_{cr,x}^2} = \frac{\pi^2 200000 \cdot 113080}{1000^2} = 223.2 \text{ kN} \\
 N_{er,y} &= \frac{\pi^2 EI_y}{L_{cr,y}^2} = \frac{\pi^2 200000 \cdot 11325}{1000^2} = 22.4 \text{ kN} \\
 N_{er,T} &= \frac{1}{k_0} (GI_t + \frac{\pi^2 EI_m}{L_{cr,T}^2}) = \frac{1}{40.8367} (76923 \cdot 48 + \frac{\pi^2 200000 \cdot 21204042}{1000^2}) = 27.3 \text{ kN} \\
 \beta &= 1 - (\frac{x_0}{r_0})^2 = 0.703 \\
 N_{er,TF} &= \frac{1}{2\beta} [N_{er,T} + N_{er,x} - \sqrt{(N_{er,T} + N_{er,x})^2 - 4\beta N_{er,T} N_{er,x}}] = 26.3 \text{ kN} \\
 N_{er} &= \min(N_{er,TF}, N_{er,y}) = 22.4 \text{ kN} \text{ (singly symmetric section)} \\
 \bar{\lambda} &= \sqrt{\frac{Af_y}{N_{er}}} = \sqrt{\frac{106 \cdot 250}{22384.7}} = 1.090 \\
 \phi &= \frac{1}{2} (1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2) = \frac{1}{2} (1 + 0.49(1.09 - 0.4) + 1.09^2) = 1.263 \\
 \chi &= \frac{1}{\phi + \sqrt{\phi^2 - 1}} = \frac{1}{1.26 + \sqrt{1.26^2 - 1}} \leq 1 \quad \chi = 0.526 \\
 N_{b,Rk} &= \chi A f_y = 0.53 \cdot 106 \cdot 250 = 14.0 \text{ kN}
 \end{aligned}$$

2 Compression resistance according to EN 1993 rules for carbon steel

2.1 Cross-section classification

Upper lip: $c/t = 15/1.0 = 15.0 > 13.6$ Class 4
 Upper flange: $c/t = 24/1.0 = 24.0 \leq 40.7$ Class 3
 Web: $c/t = 72/1.0 = 72.0 > 40.7$ Class 4
 Lower flange: $c/t = 24/1.0 = 24.0 \leq 40.7$ Class 3
 Lower lip: $c/t = 15/1.0 = 15.0 > 13.6$ Class 4
 Class 4 cross-section.

2.2 Gross cross-section

$$\begin{aligned} A_{\text{real}} &= 145 \text{ mm}^2 \\ A_{g,sh} &= \sum_{i=1}^m b_i t_i = 150 \text{ mm}^2 \\ I_{g,sh,x} &= 118246 \text{ mm}^2 \\ I_{g,sh,y} &= 15307 \text{ mm}^2 \\ &\quad \sum_{j=1}^n r_j \frac{t_j}{\pi} \\ \delta &= 0.43 \frac{\sum_{i=1}^{l-1} b_{p,i}}{\sum_{i=1}^m b_{p,i}} = 0.036 \text{ (EN 1993-1-3 (5.1))} \\ A_g &= A_{g,sh}(1 - \delta) = 150(1 - 0.036) = 145 \text{ mm}^2 \\ I_{g,x} &= I_{g,sh,x}(1 - 2\delta) = 118246(1 - 2 \cdot 0.036) = 109711 \text{ mm}^4 \\ I_{g,y} &= I_{g,sh,y}(1 - 2\delta) = 15307(1 - 2 \cdot 0.036) = 14202 \text{ mm}^4 \end{aligned}$$

2.3 Effective cross-section

$\chi_d = 1.000$ after 1 iterations

2.3.1 Upper lip

$$\begin{aligned} k_\sigma &= 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p &= \frac{b/t}{28.4\epsilon\sqrt{k_\sigma}} = \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.782 \\ \text{for outstanding element and } \bar{\lambda}_p &> 0.748 \\ \rho &= \frac{\bar{\lambda}_p - 0.188}{\bar{\lambda}_p^2} = \frac{0.78 - 0.188}{0.78^2} = 0.971 \text{ (EN 1993-1-5 (4.3))} \end{aligned}$$

2.3.2 Web

$$\begin{aligned} k_\sigma &= 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p &= \frac{b/t}{28.4\epsilon\sqrt{k_\sigma}} = \frac{70/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 1.276 \\ \text{for internal element and } \bar{\lambda}_p &> 0.673 \\ \rho &= \frac{\bar{\lambda}_p - 0.055(3+\psi)}{\bar{\lambda}_p^2} = \frac{1.28 - 0.055(3+1.0)}{1.28^2} = 0.649 \text{ (EN 1993-1-5 (4.2))} \end{aligned}$$

2.3.3 Lower lip

$$k_\sigma = 0.430 \text{ (EN 1993-1-5, Table 4.2)}$$

$$\bar{\lambda}_p = \frac{b/t}{28.4c\sqrt{k_\sigma}} = \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.782$$

for outstanding element and $\bar{\lambda}_p > 0.748$

$$\rho = \frac{\bar{\lambda}_p - 0.188}{\bar{\lambda}_p^2} = \frac{0.782 - 0.188}{0.782^2} = 0.971 \text{ (EN 1993-1-5 (4.3))}$$

2.3.4 The effect of edge stiffeners

$$\sigma_{com,Ed} = f_y = 250.000 \text{ MPa}$$

$$k_f = \frac{A_{st}}{A_{st}} = \frac{26.6}{26.6} = 1.000$$

$$K = \frac{E t^3}{4(1-\nu^2)} \cdot \frac{1}{b_1^2 h_w + b_1^3 + 0.5b_1 b_2 h_w k_f} = \frac{200000 \cdot 1.0^3}{4(1-0.3^2)} \cdot \frac{1}{21^2 \cdot 72 + 21^3 + 0.5 \cdot 21 \cdot 21 \cdot 72 \cdot 1} = 0.94$$

$$\sigma_{cr,s} = \frac{2\sqrt{K E I_s}}{A_s} = \frac{2\sqrt{0.9 \cdot 200000 \cdot 611}}{26.6} = 804.7 \text{ MPa}$$

$$\bar{\lambda}_d = \sqrt{\frac{f_y}{\sigma_{cr,s}}} = \sqrt{\frac{250.0}{804.7}} = 0.557$$

$\chi_d = 1.0$ for $\bar{\lambda}_d \leq 0.65$

$$A_{s,red} = \chi_d A_s = 1.000 \cdot 26.6 = 24.2 \text{ mm}^2$$

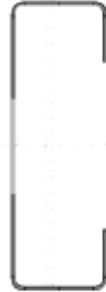


Figure 2: Effective section of Lipped channel 24.0x72.0x15.0 1.0 mm

2.3.5 Sectional properties

$$A_{eff} = 119 \text{ mm}^2$$

$$I_{x,eff} = 116630 \text{ mm}^4$$

$$I_{y,eff} = 12948 \text{ mm}^4$$

$$e_x = 1.61 \text{ mm}$$

2.4 Member buckling resistance

Buckling curve d, $\alpha = 0.76$, $\bar{\lambda}_0 = 0.2 i_0 = \sqrt{i_x^2 + i_y^2 + x_0^2} = \sqrt{31.3^2 + 10.4^2 + 22.3^2} = 39.8 \text{ mm}$

$$N_{er,x} = \frac{\pi^2 EI_x}{L_{cr,x}^2} = \frac{\pi^2 200000-116630}{1000^2} = 230.2 \text{ kN}$$

$$N_{er,y} = \frac{\pi^2 EI_y}{L_{cr,y}^2} = \frac{\pi^2 200000-12948}{1000^2} = 25.6 \text{ kN}$$

$$N_{er,T} = \frac{1}{i_0^2} (GI_t + \frac{\pi^2 EI_w}{L_{cr,T}^2}) = \frac{1}{39.767^2} (76923 \cdot 48 + \frac{\pi^2 200000-21204042}{1000^2}) = 28.8 \text{ kN}$$

$$\beta = 1 - (\frac{x_0}{r_0})^2 = 0.686$$

$$N_{er,TF} = \frac{1}{2\beta} [N_{er,T} + N_{er,x} - \sqrt{(N_{er,T} + N_{er,x})^2 - 4\beta N_{er,T} N_{er,x}}] = 27.6 \text{ kN}$$

$$N_{er} = \min(N_{er,TF}, N_{er,y}) = 25.6 \text{ kN} \text{ (singly symmetric section)}$$

$$\bar{\lambda} = \sqrt{\frac{A_f I_y}{N_{er}}} = \sqrt{\frac{119.250}{25558.9}} = 1.081$$

$$\phi = \frac{1}{2} (1 + \alpha(\bar{\lambda} - \lambda_0) + \bar{\lambda}^2) = \frac{1}{2} (1 + 0.76(1.08 - 0.2) + 1.08^2) = 1.418$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} = \frac{1}{1.42 + \sqrt{1.42^2 - 1.08^2}} \leq 1 \quad \chi = 0.428$$

$$N_{b,Rk} = \chi A f_y = 0.43 \cdot 119 \cdot 250 = 12.8 \text{ kN}$$

3 Compression resistance according to EN 1993 rules for stainless steel modified by Talja and Salmi

3.1 Gross cross-section

$$\begin{aligned} A_{real} &= 145 \text{ mm}^2 \\ A_{g,sh} &= \sum_{i=1}^m b_i t_i = 150 \text{ mm}^2 \\ I_{g,sh,x} &= 118246 \text{ mm}^4 \\ I_{g,sh,y} &= 15307 \text{ mm}^4 \\ &\quad \sum_{j=1}^n r_j \frac{\pi}{4t} \\ \delta &= 0.43 \frac{\sum_{i=1}^{j-1} b_i t_i}{\sum_{i=1}^n b_i t_i} = 0.036 \text{ (EN 1993-1-3 (5.1))} \end{aligned}$$

$$\begin{aligned} A_g &= A_{g,sh}(1 - \delta) = 150(1 - 0.036) = 145 \text{ mm}^2 \\ I_{g,x} &= I_{g,sh,x}(1 - 2\delta) = 118246(1 - 2 \cdot 0.036) = 109711 \text{ mm}^4 \\ I_{g,y} &= I_{g,sh,y}(1 - 2\delta) = 15307(1 - 2 \cdot 0.036) = 14202 \text{ mm}^4 \end{aligned}$$

3.2 Member buckling resistance

$$\begin{aligned} \alpha &= 0.49, \bar{\lambda}_0 = 0.4 \\ i_0 &= \sqrt{i_x^2 + i_y^2 + x_0^2} = \sqrt{28.6^2 + 10.3^2 + 22.3^2} = 37.7 \text{ mm} \\ N_{cr,x} &= \frac{\pi^2 EI_x}{L_{cr,x}^2} = \frac{\pi^2 200000 \cdot 118246}{1000^2} = 233.4 \text{ kN} \\ N_{cr,y} &= \frac{\pi^2 EI_y}{L_{cr,y}^2} = \frac{\pi^2 200000 \cdot 15307}{1000^2} = 30.2 \text{ kN} \\ N_{cr,T} &= \frac{1}{i_0^2} (GI_t + \frac{\pi^2 EI_w}{L_{cr,w}^2}) = \frac{1}{37.655^2} (76923 \cdot 48 + \frac{\pi^2 200000 \cdot 21204042}{1000^2}) = 32.1 \text{ kN} \\ \beta &= 1 - (\frac{x_0}{r_0})^2 = 0.650 \\ N_{cr,TF} &= \frac{1}{2\beta} [N_{cr,T} + N_{cr,x} - \sqrt{(N_{cr,T} + N_{cr,x})^2 - 4\beta N_{cr,T} N_{cr,x}}] = 30.5 \text{ kN} \\ N_{cr} &= \min(N_{cr,TF}, N_{cr,y}) = 30.2 \text{ kN (singly symmetric section)} \\ \bar{\lambda} &= \sqrt{\frac{A_f y}{N_{cr}}} = \sqrt{\frac{145 \cdot 250}{30214.9}} = 1.095 \\ \phi &= \frac{1}{2} (1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2) = \frac{1}{2} (1 + 0.49(1.09 - 0.4) + 1.09^2) = 1.269 \\ \chi &= \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} = \frac{1}{1.27 + \sqrt{1.27^2 - 1.09^2}} \leq 1 \chi = 0.523 \end{aligned}$$

3.3 Cross-section classification

Upper lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Upper flange: $c/t = 24/1.0 = 24.0 \leq 29.0$ Class 3
 Web: $c/t = 72/1.0 = 72.0 > 29.0$ Class 4
 Lower flange: $c/t = 24/1.0 = 24.0 \leq 29.0$ Class 3
 Lower lip: $c/t = 15/1.0 = 15.0 > 11.3$ Class 4
 Class 4 cross-section.

3.4 Effective cross-section

$\chi_d = 1.000$ after 1 iterations

3.4.1 Upper lip

$$k_\sigma = 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p = \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = \sqrt{0.523} \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.566 \\ \text{for outstanding element } \rho = 1 \text{ (EN 1993-1-4)}$$

3.4.2 Web

$$k_\sigma = 4.000 \text{ (EN 1993-1-5, Table 4.1)} \\ \bar{\lambda}_p = \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = \sqrt{0.523} \frac{70/1.0}{28.4 \cdot 0.97 \cdot \sqrt{4.0}} = 0.922 \\ \text{for internal element } \rho = \frac{0.722}{\lambda_p^2} - \frac{0.125}{\lambda_p^2} = \frac{0.722}{0.32} - \frac{0.125}{0.922} = 0.636 \text{ (EN 1993-1-4)}$$

3.4.3 Lower lip

$$k_\sigma = 0.430 \text{ (EN 1993-1-5, Table 4.2)} \\ \bar{\lambda}_p = \sqrt{\chi} \frac{b/t}{28.4c\sqrt{k_\sigma}} = \sqrt{0.523} \frac{14/1.0}{28.4 \cdot 0.97 \cdot \sqrt{0.4}} = 0.566 \\ \text{for outstanding element } \rho = 1 \text{ (EN 1993-1-4)}$$

3.4.4 The effect of edge stiffeners

$$\sigma_{com,Ed} = f_y = 250.000 \text{ MPa} \\ k_f = \frac{A_{sf}}{A_{s1}} = \frac{27.0}{27.0} = 1.000 \\ K = \frac{E t^3}{4(1-\nu^2) \cdot b_1^2 h_w + b_1^2 + 0.5b_1 b_2 h_w k_f} = \frac{200000 \cdot 1.0^3}{4(1-0.3^2) \cdot 21^2 \cdot 72 + 21^2 + 0.5 \cdot 21 \cdot 21 \cdot 72 \cdot 1} = 0.93 \\ \sigma_{cr,s} = \frac{2\sqrt{K E I_s}}{A_s} = \frac{2\sqrt{0.9 \cdot 200000 \cdot 657}}{27.0} = 820.5 \text{ MPa} \\ \bar{\lambda}_d = \sqrt{\frac{f_y}{\sigma_{cr,s}}} = \sqrt{\frac{250.0}{820.5}} = 0.552 \\ \chi_d = 1.0 \text{ for } \bar{\lambda}_d \leq 0.65 \\ A_{s,red} = \chi_d A_s = 1.000 \cdot 27.0 = 24.5 \text{ mm}^2$$

3.4.5 Sectional properties

$$A_{eff} = 119 \text{ mm}^2 \\ I_{x,eff} = 116851 \text{ mm}^4 \\ I_{y,eff} = 13003 \text{ mm}^4 \\ e_x = 1.78 \text{ mm} \\ N_{b,Rk} = \chi A f_y = 0.52 \cdot 119 \cdot 250 = 15.6 \text{ kN}$$



Figure 3: Effective section of Lipped channel 24.0x72.0x15.0 1.0 mm

4 Compression resistance using DSM according to Becque et al. for EN 1993

$$A_{real} = 145 \text{ mm}^2$$

$$A_{g,sh} = \sum_{i=1}^m b_i t_i = 150 \text{ mm}^2$$

$$I_{g,sh,x} = 118246 \text{ mm}^4$$

$$I_{g,sh,y} = 15307 \text{ mm}^4$$

$$\delta = 0.43 \frac{\sum_{i=1}^{n-1} r_j \frac{t_j}{w}}{\sum_{i=1}^n b_{p,i}} = 0.036 \text{ (EN 1993-1-3 (5.1))}$$

$$A_g = A_{g,sh}(1 - \delta) = 150(1 - 0.036) = 145 \text{ mm}^2$$

$$I_{g,x} = I_{g,sh,x}(1 - 2\delta) = 118246(1 - 2 \cdot 0.036) = 109711 \text{ mm}^4$$

$$I_{g,y} = I_{g,sh,y}(1 - 2\delta) = 15307(1 - 2 \cdot 0.036) = 14202 \text{ mm}^4$$

4.1 Distortional buckling

$$k_f = \frac{A_{g,sh}}{A_{p,1}} = \frac{39.0}{39.0} = 1.000$$

$$K = \frac{E t^3}{4(1-\nu^2)} \cdot \frac{1}{b_1^2 h_w + b_1^4 + 0.5 b_1 b_2 h_w k_f} = \frac{200000 \cdot 1.0^3}{4(1-0.3^2)} \cdot \frac{1}{17^2 \cdot 72 + 17^3 + 0.5 \cdot 17 \cdot 17 \cdot 72 \cdot 1} = 1.60$$

$$\sigma_{cr,s} = \frac{2\sqrt{K E t^3}}{A_s} = \frac{2\sqrt{1.6 \cdot 200000 \cdot 80^2}}{39.0} = 821.0 \text{ MPa}$$

$$\lambda = \sqrt{\frac{f_y}{\sigma_{cr}}} = \sqrt{\frac{250}{821}} = 0.552$$

$$f_{y,red} = (\frac{0.90}{0.551 \cdot 10} - \frac{0.20}{0.552 \cdot 10}) f_y = 248 \text{ MPa for } \lambda > 0.533$$

$$N_b = f_{y,red} A = 248 \cdot 145 = 35.9 \text{ kN}$$

4.2 Overall and local buckling interaction

$$\sigma_{er} = k \frac{\pi^2 E}{12(1-\nu)^2} \left(\frac{1}{b}\right)^2 = 4.0 \frac{\pi^2 200000}{12(1-0.3)^2} \left(\frac{1.0}{66}\right)^2 = 308 \text{ MPa}$$

(for Web) $\alpha = 0.49$, $\bar{\lambda}_0 = 0.4$

$$i_0 = \sqrt{i_x^2 + i_y^2 + x_0^2} = \sqrt{28.6^2 + 10.3^2 + 22.3^2} = 37.7 \text{ mm}$$

$$N_{er,x} = \frac{\pi^2 EI_x}{L_{er,x}^2} = \frac{\pi^2 200000 \cdot 118246}{1000^2} = 233.4 \text{ kN}$$

$$N_{er,y} = \frac{\pi^2 EI_y}{L_{er,y}^2} = \frac{\pi^2 200000 \cdot 15307}{1000^2} = 30.2 \text{ kN}$$

$$N_{er,T} = \frac{1}{\bar{\lambda}_0} (GI_t + \frac{\pi^2 EI_w}{L_{er,T}^2}) = \frac{1}{37.655^2} (76923 \cdot 48 + \frac{\pi^2 200000 \cdot 21204042}{1000^2}) = 32.1 \text{ kN}$$

$$\beta = 1 - (\frac{r_0}{r_0})^2 = 0.650$$

$$N_{er,TF} = \frac{1}{2\beta} [N_{er,T} + N_{er,x} - \sqrt{(N_{er,T} + N_{er,x})^2 - 4\beta N_{er,T} N_{er,x}}] = 30.5 \text{ kN}$$

$$N_{er} = \min(N_{er,TF}, N_{er,y}) = 30.2 \text{ kN} \text{ (singly symmetric section)}$$

$$\bar{\lambda} = \sqrt{\frac{A f_u}{N_{er}}} = \sqrt{\frac{145 \cdot 250}{30214.9}} = 1.095$$

$$\phi = \frac{1}{2}(1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2) = \frac{1}{2}(1 + 0.49(1.09 - 0.4) + 1.09^2) = 1.269$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} = \frac{1}{1.27 + \sqrt{1.27^2 - 1.09^2}} \leq 1 \quad \chi = 0.523$$

$$\lambda = \sqrt{\frac{\chi f_y}{\sigma_{er}}} = \sqrt{\frac{0.523 \cdot 250}{308}} = 0.651$$

$$f_{y,red} = \left(\frac{0.95}{0.65^{1.00}} - \frac{0.20}{0.65^{2.00}} \right) f_y = 247 \text{ MPa for } \lambda > 0.550$$

$$N_b = \chi f_{y,red} A = 0.523 \cdot 247 \cdot 145 = 18.7 \text{ kN}$$

5 Compression resistance using CSM

$$\sigma_{cr} = k \frac{\pi^2 E}{12(1-\nu)^2} \left(\frac{t}{b}\right)^2 = 4.0 \frac{\pi^2 200000}{12(1-0.3)^2} \left(\frac{1.0}{66}\right)^2 = 308 \text{ MPa}$$

$$\lambda_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \sqrt{\frac{250}{308}} = 0.901$$

$$\lambda_{cs} = \max(\lambda_p) = 0.901 \text{ for Web}$$

$$\frac{f_{csm}}{f_y} = \frac{0.25}{0.901} = 0.365 \leq (15, \frac{0.1\epsilon_u}{\epsilon_y} = \frac{0.1-0.286}{0.001})$$

$$f_{csm} = f_y + E_{sh} \epsilon_y \left(\frac{f_{csm}}{f_y} - 1 \right) = 250 + 2355 \cdot 0.001 (0.365 - 1) = 248.129 \text{ MPa}$$

$$N_{csm,Rk} = f_{csm} A = 250 \cdot 145 = 35.941 \text{ kN}$$

6 Effective sections reduction factors

EN 1993-1-4 width reduction

	0.5 mm	1.0 mm	1.5 mm
Web	0.264	0.489	0.676
Upper lip	0.636	0.901	1.000
Upper flange	0.802	1.000	1.000
Lower flange	0.802	1.000	1.000
Lower lip	0.636	0.901	1.000

EN 1993-1-4 thickness reduction

	0.5 mm	1.0 mm	1.5 mm
Upper lip	0.825	1.000	1.000
Upper flange	0.825	1.000	1.000
Lower flange	0.825	1.000	1.000
Lower lip	0.825	1.000	1.000

EN 1993-1-1 width reduction

	0.5 mm	1.0 mm	1.5 mm
Web	0.358	0.649	0.872
Upper lip	0.660	0.971	1.000
Lower lip	0.660	0.971	1.000

EN 1993-1-1 thickness reduction

	0.5 mm	1.0 mm	1.5 mm
Upper lip	0.828	1.000	1.000
Upper flange	0.828	1.000	1.000
Lower flange	0.828	1.000	1.000
Lower lip	0.828	1.000	1.000