DESIGN GUIDES FOR HIGH STRENGTH STRUCTURAL HOLLOW SECTIONS MANUFACTURED BY SSAB - FOR EN 1090 APPLICATIONS

SSAB produces a wide variety of hollow sections in different steel grades according to European standard EN 10219. The standard EN 10219 covers steel grades S235 – S460, but our offering goes beyond this up to steel grade S900. These design guides show how to make most of the high strength hollow sections produced by SSAB in design according to Eurocode 3.

DESIGN GUIDE FOR COLD-FORMED S500MH – S700MH STRUCTURAL HOLLOW SECTIONS MANUFACTURED BY SSAB

This document gives guidance on how to use the high strength grades in design despite they are lacking a product standard. Also material requirements given by Eurocode 3 are covered. The use of S500MH-S700MH structural hollow sections requires that the material properties should be specified in the component specification. The design guide can be used for the project-based approval of the high-strength structural hollow sections which are not covered by EN 10219, a reference standard in EN 1090.

AXIAL RESISTANCE OF DOUBLE GRADE (S355, S420) HOLLOW SECTIONS MANUFACTURED BY SSAB

In this study the buckling curve for double grade hollow section has been determined experimentally. It is shown that within specified geometrical limits curve b instead of curve c according to Eurocode 3 can be utilized. A designer can utilize the improved buckling curve in the design and it is suggested to include this design guide in the design documentation.

Both of these studies were conducted as a joint project between Tampere University of Technology and Lappeenranta University of Technology. The validity of results is verified by professors Timo Björk and Markku Heinisuo. These design guides are valid only to hollow sections manufactured by SSAB. For further information please contact SSAB sales or technical customer service.

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26.09.2014

Design guide for cold-formed S500MH - S700MH structural hollow sections manufactured by SSAB

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Introduction

This guide is needed because the standard for steel grades S500MH - S700MH does not exist. Also, all these steel materials do not meet the the requirement of EN 1993-1-12:

- Ultimate strain ε_u, yield strain $\varepsilon_y = f_y/E$: $\varepsilon_u \geq 15\ \varepsilon_y$.

which is connected to the plastic design. This guide is meant for project approvals when using these steel grades in constructions.

Member design

Tubular structures can be designed using the global elastic analysis for the structures, frames. This means that the members and the joints are modeled using elastic stiffness for the global analysis. The plastic global analysis allowing redistribution of the stress resultants is not used for these structures. The resistance checks of members after running the global analysis can be done using elastic or plastic member properties depending on the cross-section class of the member as defined in EN 1993-1-1 and in EN 1993-1-12. By testing of beams in bending using the most critical cross-section for S700MH (at the upper limit of the cross-section class 2) it has been shown that the plastic bending moment can be reached safely at the ultimate limit state. The test report is the reference [1] and the corresponding summary of the tests is the reference [2]. Figure 1 illustrates the bending tests.

Figure 1. Bending test and corresponding failure mode for tubular S700MH member.

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It can be seen, that the failure mode was as expected using the equations of the Eurocodes: Local buckling at the top chord of the member.

Joint design

The global analysis is elastic, as stated above, meaning that we do not use the plastic hinge theory in the global analysis. When considering the joint design after the global analysis there exist two different situations:

- Bolted joints which are made using plates made of different steel grades than the tubular members and using bolts;
- Welded joints where tubular members are welded to tubular members, as in trusses.

It has been shown in the literature [3] that the component method of EN 1993-1-8 is suitable up to such steel grades as S690 in plates and M12.9 for bolts. In such cases the stiffness of the joints for the global analysis should be defined as stated in EN 1993-1-8.

Welded joints of tubular structures

Welded joints of tubular structures are modeled to the global analysis using hinges at the ends of joined members without any rotational stiffness and supposing that the joints are absolutely rigid with respect to other displacements. After the global analysis the resistances of the joints are checked using the equations which are mainly based on the yield line theory. This means that it is supposed, that at the joints there exist enough ductility so that the yield lines may develop at the joints. The proof of the latest hypothesis can be done using FEM analyses which are validated by the tests or purely based on tests, which is in the line with the general rules of Eurocodes. In recent tests completed in Lappeenranta University of Technology (LUT) under RFCS project “Rules on high strength steels” [4] have been shown the relevancy of the existing rules in EN 1993-1-8 and in EN 1993-1-12 for tubular structures made of S500MH - S700 MH steel grades.

There are many parameters in these joints. The most important are:

- Type of the joint, T-, K- and KT-joints being the most important in trusses.
- Gap g at the joint;
- Angle θ of the joined member to the main member;
- Ratio $\beta = b_i/b_0$ of the joined members;
- Ratio $\gamma = b_0/(2t_0)$ of the main member;
- Cross-section slenderness ratios b_i/t_i and h_i/t_i for each member;
- Eccentricity of the joint.

There are many failure modes which should be checked in the design, such as:

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- Chord face failure;
- Brace failure;
- Chord side wall buckling;
- Chord shear;
- Punching shear;
- Chord side wall crushing;
- Chord distortional failure.

All failure modes are not present in all joints. The resistance check of KT-joints is done using the checks of series of K-joints. The K-joint should be designed as two T-joints in some cases. T-joints and K-joints are the basic joint types to be considered. The potential failure modes which are not included in current design codes are not considered in this approval document.

The recent tests [4] dealt with 20 X-joints and 20 K-joints made of S500MH and S700MH steels. The parameters which varied in the tests were the gap *g* (minimum/maximum allowed), the ratio *b* (0.53-0.83). The ratio γ was in most of the tests 15 and in some tests 10. The ratio value $\gamma = 15$ is near by the upper limit of this ratio. The upper value means the most slender main member at the joint. The variations of these three parameters cover very well the values needed in the structural design of these joints.

The angle θ was a constant 60^o at each test of K-joints. The brace angle $\theta = 60°$ is the lower limit value, which can be welded by using fillet welds. The gap side welds of brace members must be carried by using bevel groove welds, if the brace angle is smaller. The design rules for bevel groove welds are simple and thus were not included in the research work. Concerning the requirements for welds parallel to chord member, the brace angle $\theta = 60^o$ is also a quite good choice. A little bit smaller angle $\theta \approx 50°$ would obtain still higher requirement for throat thickness, but considering the capacity of the joint, the smaller the angle the higher the capacity. Consequently, the smaller angles ($\theta \approx 40...50°$) obtain more efficient joints and are therefore favorable but not so critical and interesting from research point of view and as compromise the investigation was focused on brace members with $\theta = 60°$.

Almost all failure modes but punching shear were observed in the tests. In K-joint tests the observed failure load (F_{test}) versus the failure load calculated based on EN 1993-1-8 (F_{EC}) without “penalty” factor 0.8 for the high strength steel joints as stated in EN 1993-1-12 in mean 1.23 (variation 0.14) for S500MH and 1.05 (variation 0.08) for S700MH. The minimum ratio in these 20 tests was 0.95. In X-joint tests these ratios were much larger. The minimum ratio was 1.16, and many ratios were over 2.0, the largest being 3.35. Figure 2 illustrates the resistance from tests versus the expected resistance using EN 1993-1-8 for K-joints and S500MH steel. More results can be found in [4].

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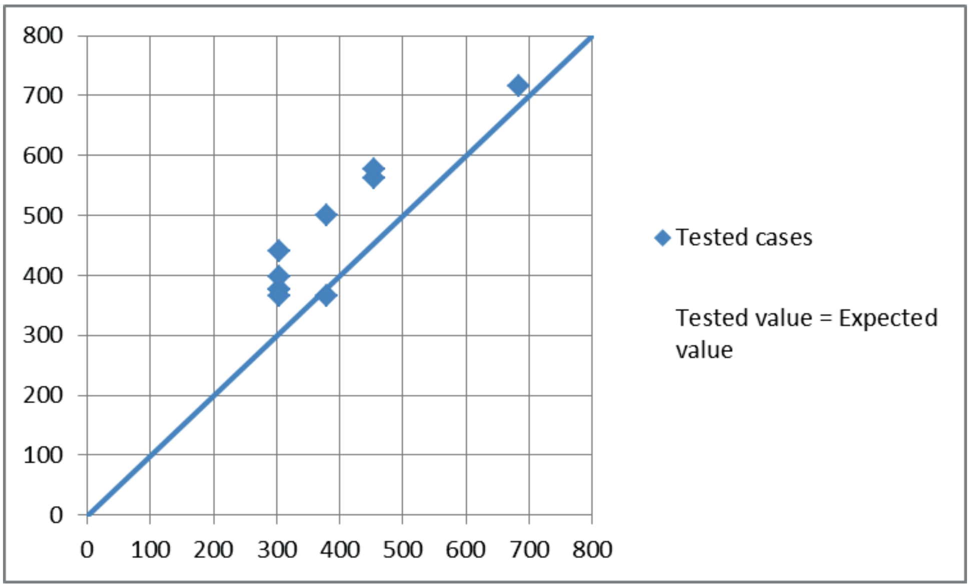

Figure 2. Tested values (kN, vertical axis) versus expected values (kN horizontal axis) for K-joints and S500MH.

Based on these tests it can be concluded that the present rules of EN 1993-1-8 and EN 1993-1-12 (with "penalty" factors) can be used safely for the welded tubular joints using steel grades S500MH - S700MH. The scope of the tests in LUT was to study a) if the "penalty" factors are needed for these joints and b) to study if these joints can be completed without using full-strength welds at the joints. These researches are going on in LUT and in the future these research questions can be answered. The test specimen in LUT included also joints where not full strength welds were used.

Using EN 1993-1-8 for the structural analysis of tubular trusses, the braces are modeled as hinge ended members. When considering the use of HSS in these structures the effect of secondary moments at braces and corresponding strains at the joint area has been proposed to be checked [5]. In the reference [6] this question has been studied and the outcome was that the strains due to this effect were at the acceptable level up to the steel grade S700 when the current requirements for eccentricity are not exceeded.

Weld design

The researches completed so far do not give any new design rules for welds, so the rules of EN 1993-1-8 and EN 1993-1-12 should be used. It should be mentioned that in recent researches in Germany they have ended to smaller correlation factors β in fillet welds for high strength steels. This means smaller required weld sizes, but these rules are not yet available in the standards.

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Summary

The design rules for S500MH - S700 MH hollow sections manufactured by SSAB based on information available up today can be summarized as:

- Use elastic global analysis;
- Member resistance is checked using elastic or plastic moment of the member. Plastic moment can be used based the cross-section classification of EN 1993-1-1 and EN 1993-1-12;
- Bolted joints are calculated using EN 1993-1-8 and EN 1993-1-12 as they are;
- The resistances of tubular welded joints can be checked using the rules of EN 1993-1-8 and EN 1993-1-12 (with “penalty” factors). The need of “penalty” factors is currently under research.
- The global analysis of trusses can be done using hinges at the ends of braces as is recommended in EN 1993-1-8.

Signatures

26.09.2014

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23.9.2014

Axial resistance of double grade (S355, S420) hollow sections manufactured by SSAB

Based on tests in LUT and statistical evaluation of the results based on EN 1990 the axial resistance of SSAB's double grade hollow sections, which fulfill the requirements of steel grades S355J2H and S420MH, can be defined using the rules of EN 1993-1-1, $f_y = 420$ MPa and

- $t \geq 3$ mm, $\bar{\lambda} \leq 1.50$ => Curve *b* (imperfection factor $\alpha = 0.34$)

with the factor $\gamma_{M1} = 1.0$.

Seinäjoki, Finland 23.9.2014

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Axial resistance of double grade (S355, S420) hollow sections manufactured by SSAB, statistical evaluation based on tests

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Introduction and scope

The structural design considered is based on the Eurocode system. The design of cold-formed hollow sections is based on EN 1993-1-1 [1] and its National Annexes. The buckling resistance of the hollow sections is defined using the rules of EN 1993-1-1 chapter 6.3: *Buckling resistance of members*. The buckling resistance $N_{b,Rd}$ is calculated as:

$$N_{b,Rd} = \frac{\chi \cdot A \cdot f_{yb}}{\gamma_{M1}} \tag{1}$$

or

$$N_{b,Rd} = \frac{\chi \cdot A_{eff} \cdot f_{yb}}{\gamma_{M1}} \tag{2}$$

where

- χ is the reduction factor for the relevant buckling curve;
- A is the cross-section area of the cross-section in the cross-section classes 1, 2 and 3;
- A_{eff} is the effective cross-section area of the cross-section in the cross-section class 4, classification is done for compression only, effective width see EN 1993-1-5;
- f_{yb} is the basic yield strength of the material;
- γ_{M1} is the material factor for buckling, recommended value $\gamma_{M1} = 1.0$.

The reduction factor χ is:

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \quad but\ \chi \leq 1.0 \tag{3}$$

and

$$\phi = 0.5 \cdot \left[1 + \alpha \cdot \left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] \tag{4}$$

$$\bar{\lambda} = \sqrt{\frac{A \cdot f_{yb}}{N_{cr}}} \tag{5}$$

or

$$\bar{\lambda} = \sqrt{\frac{A_{eff} \cdot f_{yb}}{N_{cr}}} \tag{6}$$

where

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- α is an imperfection factor, buckling curve *c* meaning value $\alpha = 0.49$ is given in EN 1993-1-1 for cold-formed hollow sections;
- N_{cr} is the elastic critical axial force for the relevant buckling mode.

The different buckling curves are shown in Fig. 1.

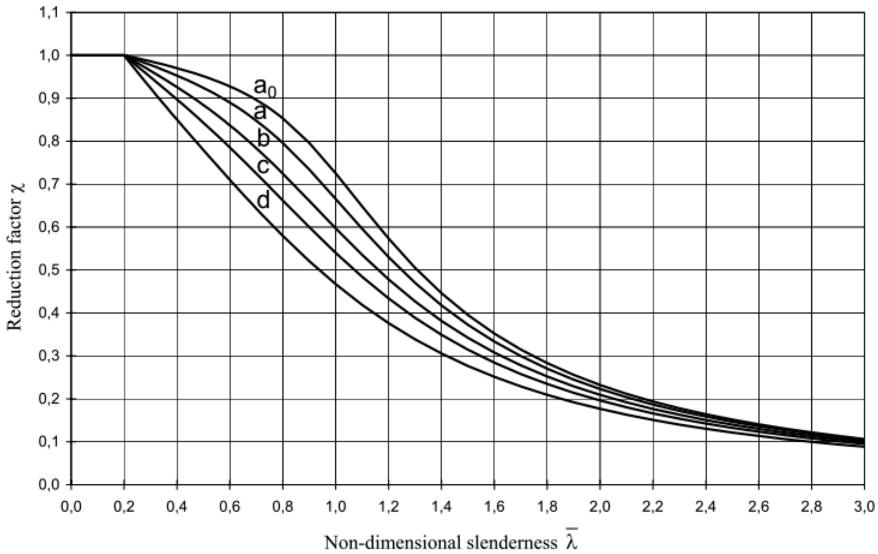

Figure 1. Bucling curves of EN 1993-1-1.

It can be seen, that there exist a plateau in all curves with small slenderness $\bar{\lambda} \le 0.2$. So, the plateau value N_{pl} may be defined based on the tests, or the goal may be the proper buckling curve for the hollow sections.

The critical axial force is

$$N_{cr} = \frac{\pi^2 \cdot E \cdot I}{L_{cr}^2} \tag{7}$$

where

- E is the elastic modulus of steel, E = 210000 MPa;
- I is the moment of inertia of the gross-section;
- L_{cr} is the buckling length of the member.

The scope of this study is to consider using the statistical evaluation of EN 1990 Annex D [2]:

- What buckling curve is the most suitable for SSAB's double grade hollow sections which fulfill the requirements of steel grades S355J2H and S420MH, meaning the nominal yield strength 420 MPa?
- The target value for the safty factor in buckling is $\gamma_{M1} = 1.0$.

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The statistical evaluation is done based on the tests completed in LUT [3]. The tests covered the range [$0.10 \leq \bar{\lambda} \leq 1.50$]. The tested profiles were:

- 50x50x2;
- 100x100x3;
- 150x150x5;
- 200x200x6;
- 300x300x8.8.

Statistical method of EN 1990

The statistical evaluation is done following strictly EN 1990 Annex D. More theoretical background can be found in [4]. Practical examples demonstrating the effects of different amount of random variables and grouping of tests to the target safety factor γ_{M1*} in the flexural buckling can be found in [5].

In this study we consider three variables as random variables X_j (j = 1, 2, 3):

- X_1 is the yield strength of steel;
- X_2 is the side length of the hollow section, only square rectangular hollow sections are considered;
- X_3 is the wall thickness of the hollow section.

All these were measured in the real test specimen and they have been reported in [3]. Other properties are considered as deterministic, including the elastic modulus. In [5] it is shown that this assumption means only marginal effect to the result, target value γ_{M1*} and moreover, it is well-known that measuring of the elastic modulus is rather complicated. So, the elastic modulus was not measured in this study.

Four values of axial forces are needed in the following:

- Experimental ultimate value of the axial load in the tests i ($i = 1, \ldots, n$) $r_{e,i}$.
- Theoretical values obtained from Eqs. (1) - (7) $r_{t,i}$. These are calculated using the measured values of yield strength, side length and wall thickness.
- Theoretical values obtained from Eqs. (1) – (7) using the nominal values $r_{nom,i}$.
- Theoretical values (resistance function g_{rt} values) obtained from Eqs. (1) – (7) using the mean values $\underline{X}_m$ for the measured variables X_j: $g_{rt}(\underline{X}_m)$.

The regression line through the origin may be used to approximate the trend, however many such lines exist. By minimization the cumulative error $\varepsilon^2 = \sum (r_{e,i} - b \cdot r_{t,i})^2$ and assuming that the variance of the residual is constant, a least square calculation can be used based on the quadrature of the residual. By setting the derivative of ε^2 with respect to b to zero, the linear regression coefficient b is found:

$$b = \frac{\sum_{i=1}^{n} r_{e,i} \cdot r_{t,i}}{\sum_{i=1}^{n} \left(r_{t,i}\right)^2} \tag{8}$$

where n is the amount of experiments. After this must be calculated

- Logarithm of the error term δ_i: Δ_i;
- Estimated value for mean value of Δ : $\overline{\Delta}$;
- Estimated value for the standard deviation σ: s;
- Estimated value for the standard deviation σ_Δ : s_Δ;
- Estimator for the coefficient of variation of the error terms δ_i: V_δ;

and those are:

$$\Delta_i = \ln\left(\frac{r_{e,1}}{b \cdot r_{t,i}}\right) = \ln \delta_i \tag{9}$$

$$\overline{\Delta} = \frac{1}{n} \cdot \sum_{i=1}^{n} \Delta_i \tag{10}$$

$$s_\Delta^2 = \frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(\Delta_i - \overline{\Delta}\right)^2 \tag{11}$$

$$V_\delta = \sqrt{\exp(s_\Delta^2) - 1} \tag{12}$$

ending up to the coefficient of variation V_δ of the error terms δ_i.

The sensitivity of the resistance function to the variability of the basic input variables is considered through the coefficient of the variation V_{rt}. The exact way to calculate this is supposing that the variables X_j are not dependent on each other:

$$V_{rt}^2 = \frac{1}{g_{rt}\left(\underline{X_m}\right)^2} \sum_{j=1}^{3} \left(\frac{\partial g_{rt}\left(X_j\right)^2}{\partial X_j} \sigma_j\right)^2 \tag{13}$$

The resistance function is rather complicated with respect to the variables X_j, so typically the values of Eq. (13) are calculated numerically using finite differences near by the mean values of the variables, as is done in [5]. However, it has bee shown in [5] that by calculating the error propagation term $V_{r,t}$ based on variations of measured dimensions and yield strengths the difference is not large (below 3 % in the target value γ_{M1*}) when the variations of measured properties are used instead of Eq. (13). Moreover, it is shown in [5] that the use of measured properties means safe side solution in the flexural buckling case.

So, in this study the simplified analysis is used, see [4]:

$$V_{rt}^2 = \sum_{j=1}^{3} V_{Xj}^2 \tag{14}$$

where V_{Xj} is the coefficient of variation of every random variable X_j:

$$V_{Xj}^2 = \frac{\sigma_{Xj}^2}{X_{jm}^2} \tag{15}$$

Often the conservative estimation $V_{rt} = 0.1$ is used. In [6] has been demostrated that it is essential to calculate the value of V_{rt} more exactly, so in this study Eq. (15) is used.

Finally, the log-normal variation coefficients are:

$$Q_{r,t} = \sqrt{\ln\left(V_{r,t}^2 + 1\right)} \tag{16}$$

$$Q_{\delta} = \sqrt{\ln\left(V_{\delta}^2 + 1\right)} \tag{17}$$

$$Q = \sqrt{\ln\left(V_{r}^2 + 1\right)} \tag{18}$$

$$V_r^2 = V_{r,t}^2 + V_{\delta}^2 \tag{19}$$

The design values of the resistance r_d is in this case with the large amount of tests ($n \geq 30$):

$$r_d = b \cdot g_{rt}\left(\underline{X_m}\right) \cdot \exp(-k_{d,\infty} \cdot Q - 0.5 \cdot Q^2) \tag{20}$$

where $k_{d,\infty} = 3.04$, as defined in EN 1990, Table D2.The required partial safety factor γ_{M1*i} for the test i is:

$$\gamma_{M1*i} = \frac{r_{nom,i}}{r_d} \tag{21}$$

It can be seen, that we get different safety factor for all tests i. The safety factor may be calculated by grouping (k = 1, …, m) the cases properly into m groups (or families) and by calculating the mean of the safety factors for the groups, as is stated in [1]. In [5] the groups are made based on different slenderness and this method is used in this study.

Fig. 2 summarizes the statistical evaluation.

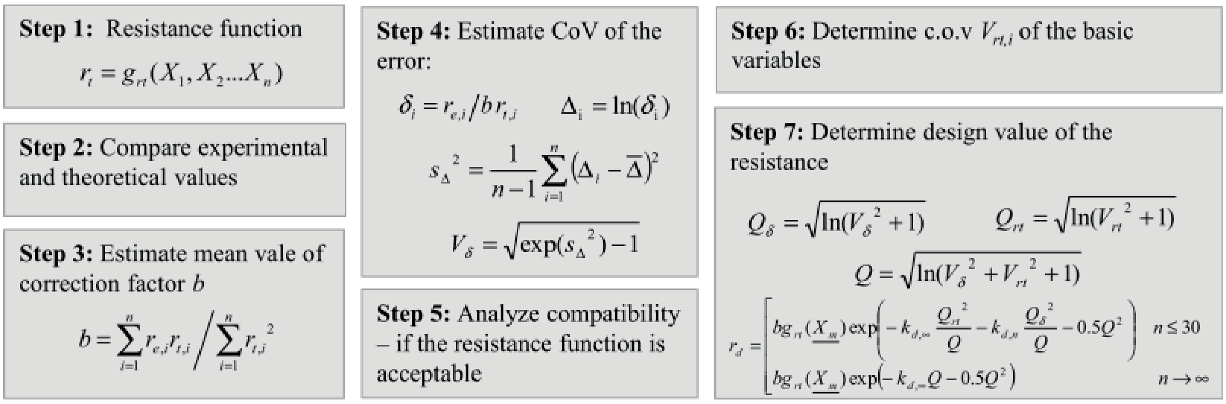

Figure 2. Statistical evaluation [5].

The **final safety factor, applicable for the design based on nominal input data is** the mean of the factors for the groups, i.e:

$$\gamma_{M*} = \sum_{k=1}^{m} \gamma_{M*k} \tag{22}$$

and

$$\gamma_{M*k} = \sum_{i=1}^{w} \gamma_{M*i} \tag{23}$$

if group k consists of w tests of all tests i. If all tests are put to one group then the result is conservative, as is shown in [5]. In [5] it is proposed the groups based on the nominal slenderness of the members. This method is used in this study. No strict rules for the slenderness limits of the groups can be found, so in this study the test cases are grouped based on the data available. The mean of coefficients b_k for groups k should be near by one, so that the theoretical resistance function describes the test data as well as possible.

Statistical analysis of tests

Column stub tests

When considering the buckling resistance of the column applying *Fig.1*, it can be seen that using the tests two way can be used to define the resistance:

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- Define plateau value (small slenderness) based on tests, or;
- Define proper buckling curve based on tests.

The plateau value can be defined using column stub tests, meaning short columns when buckling is not the present. In this project 18 column stub tests were done. In this case the columns with the slenderness $\bar{\lambda} = 0.10... 0.30$ are considered as column stub tests. The test results are given in Table 1. Index e refers to experiments and index t to theory. In the first column are given the cross-section classifications based measured dimensions and yield strength. PL4 means the cross-section class 4. The cross-section class for 100x100x3 and for 200x200x6 was 3 using the nominal dimensions and yield strength 420 MPa. Theoretical resistances based on measured or mean data were calculated for these cases based on the cross-section class 4, meaning the use of effective widths. For 100x100x3 the reduction factor for the cross-section area was 0.91 and for 200x200x6 the reduction was 0.93. The coding of the tests is the same as in [3].

Table 1. Column stub test results.

$Class_{test}$	λ_{nom}	*Test*	$f_{y,e}$	E_e	h_e	b_e	t_e	L_{cr}	$r_{e,i}$	$r_{t,i}$
-	-	-	*MPa*	*MPa*	*mm*	*mm*	*mm*	*mm*	*kN*	*kN*
PL1-2	0,10	B15_1	522	210000	49,75	49,75	2,02	137,7	227	196
PL1-2	0,10	B15_2	522	210000	49,75	49,75	1,94	137,4	229	188
PL1-2	0,10	B15_3	522	210000	49,75	49,75	2,02	137,7	215	195
PL4	0,10	B11_1	528	210000	100,10	100,10	2,94	276	540	517
PL4	0,10	B11-2	528	210000	100,10	100,10	2,93	276	557	515
PL4	0,10	B11_3	528	210000	100,10	100,10	2,94	276	540	517
PL3	0,10	B7_1	519	210000	150,25	150,25	4,94	412	1570	1457
PL3	0,10	B7_2	519	210000	150,25	150,25	4,94	413	1545	1456
PL3	0,10	B7_3	519	210000	150,25	150,25	4,94	413	1514	1457
PL4	0,10	B3_1	496	210000	200,05	200,05	5,94	553	2307	2021
PL4	0,10	B3_2	496	210000	200,10	200,10	5,93	553	2229	2015
PL4	0,10	B3_3	496	210000	200,10	200,10	5,91	553	2168	2004
PL3	0,10	B1_1	461	210000	300,10	300,10	8,60	827	4341	4516
PL3	0,10	B1-2	461	210000	300,10	300,10	8,58	825	4536	4503
PL3	0,10	B1_3	461	210000	300,10	300,10	8,58	825,5	4453	4503
PL3	0,30	B0_1	461	210000	300,10	300,10	8,60	2498	4245	4317
PL3	0,30	B0_2	461	210000	300,10	300,10	8,58	2499	4161	4316
PL3	0,30	B0_3	461	210000	300,10	300,10	8,58	2498	4395	4317

The experimental values $r_{e,i}$ divided by the theoretical values $r_{t,i}$ calculated using measured dimensions and yield strenght are given in *Fig. 3*.

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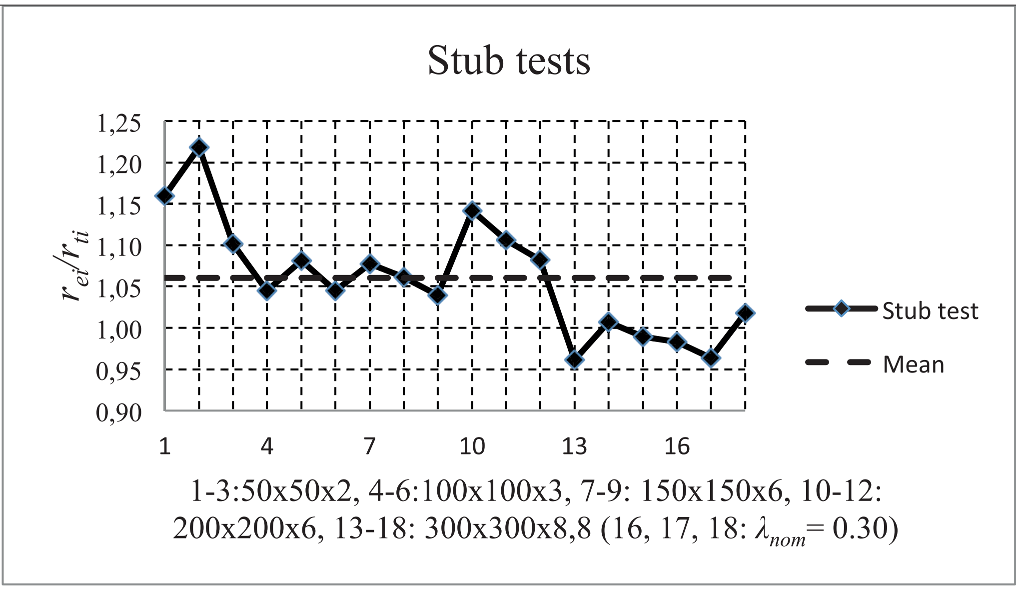

Figure 3. Column stub tests.

It can be seen that rather low values for the ratio $r_{e,i}/r_{t,i}$ are present especially for the cross-section 300x300x8.8, test numbers 13-18. Using these results the control of the plateau is not reasonable. Instead, the evaluation of the buckling curve based on other tests will be done.

Evaluation of the buckling curve

Firstly, the used excel application was verified using the data of [4], Table 5.2. The used excel gave the same results than the reference.

The tests using the cross-section 50x50x2 are considered separately, because the results in those tests differed considerable from other test results. Also, one test B2_2 (300x300x8.8) is omitted from the evaluation because in test arrangements there were problems with the support in this test.

The results of 29 tests are given in Table 2.

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Table 2. Results of buckling tests.

$Class_{test}$	λ_{nom}	Test	$f_{y,e}$	E_e	h_e	b_e	t_e	L_{cr}	$r_{e,i}$	$r_{t,i}$
-	-	-	MPa	MPa	mm	mm	mm	mm	kN	kN
PL4	0,50	B12_1	528	210000	100,10	100,10	2,94	1382	520	452
PL4	0,50	B12_2	528	210000	100,10	100,10	2,93	1383	519	450
PL4	0,50	B12_3	528	210000	100,10	100,10	2,94	1383	515	453
PL4	1,00	B13_1	528	210000	100,20	100,20	2,93	2766	294	293
PL4	1,00	B13_2	528	210000	100,10	100,10	2,94	2766	306	294
PL4	1,00	B13_3	528	210000	100,20	100,20	2,93	2766	283	293
PL4	1,50	B14_1	528	210000	100,05	100,05	2,94	4150	172	164
PL4	1,50	B14_2	528	210000	100,10	100,10	2,93	4150	195	164
PL4	1,50	B14_3	528	210000	100,10	100,10	2,94	4149	171	165
PL3	0,50	B8_1	519	210000	150,25	150,25	4,94	2066	1372	1252
PL3	0,50	B8_2	519	210000	150,25	150,25	4,94	2066	1379	1252
PL3	0,50	B8_3	519	210000	150,25	150,25	4,94	2066	1370	1252
PL3	1,00	B9_1	519	210000	150,25	150,25	4,94	4134	790	772
PL3	1,00	B9_2	519	210000	150,25	150,25	4,94	4134	823	772
PL3	1,00	B9_3	519	210000	150,25	150,25	4,94	4134	797	772
PL3	1,50	B10_1	519	210000	150,25	150,25	4,94	6201	435	420
PL3	1,50	B10_2	519	210000	150,25	150,25	4,94	6201	459	420
PL3	1,50	B10_3	519	210000	150,25	150,25	4,94	6201	458	420
PL4	0,50	B4_1	496	210000	200,10	200,10	5,94	2767	2156	1773
PL4	0,50	B4_2	496	210000	200,10	200,10	5,93	2767	2185	1769
PL4	0,50	B4_3	496	210000	200,10	200,10	5,91	2767	2118	1759
PL4	0,71	B5_1	496	210000	200,10	200,10	5,91	3949	1837	1532
PL4	0,71	B5_2	496	210000	200,25	200,25	5,94	3949	1808	1544
PL4	0,71	B5_3	496	210000	200,10	200,10	5,94	3949	1804	1543
PL4	1,13	B6_1	496	210000	200,10	200,10	5,93	6249	1106	1005
PL4	1,13	B6_2	496	210000	200,10	200,10	5,94	6250	1084	1007
PL4	1,13	B6_3	496	210000	200,10	200,10	5,91	6250	1077	1001
PL3	0,48	B2_1	461	210000	300,10	300,10	8,60	3948	4310	3996
PL3	0,48	B2_3	461	210000	300,10	300,10	8,58	3948	4356	3984

Consider firstly the fitting of the test data to different buckling curves:

- Curve *a*: imperfection factor $\alpha = 0.21$;
- Curve *b*: imperfection factor $\alpha = 0.34$;
- Curve *c*: imperfection factor $\alpha = 0.49$.

The measure for the fitting is the linear regression coefficient *b* as defined in Eq. (8). The results are given in *Figs. 4 - 6*.

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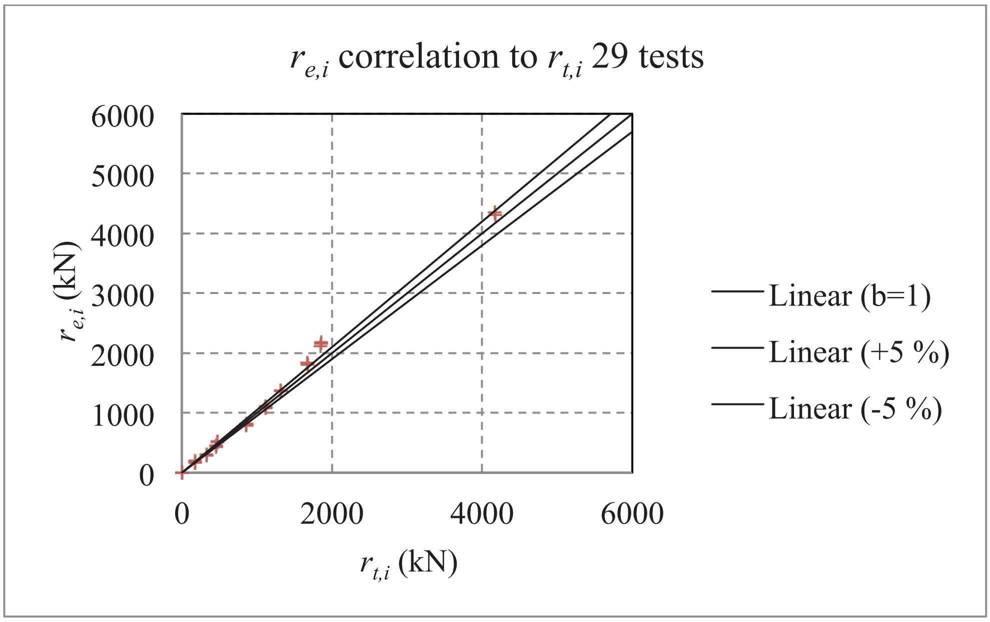

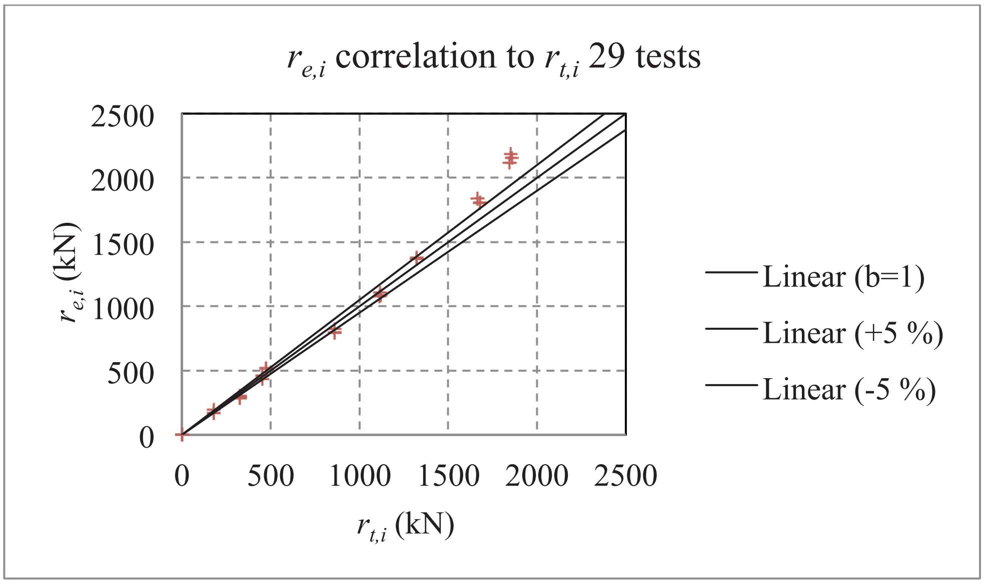

Figure 4. Fitting of data to curve a, b = 1.06.

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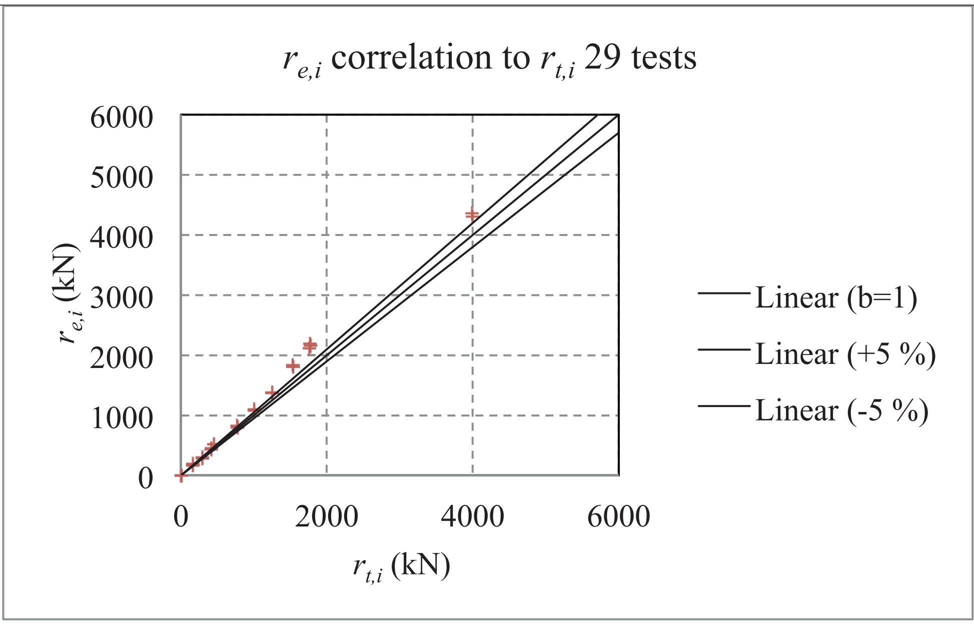


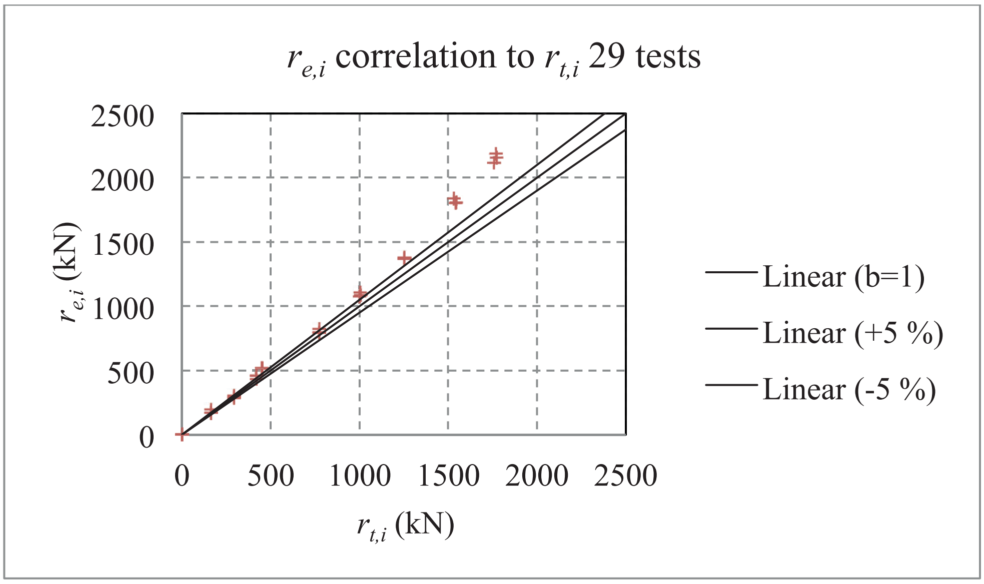
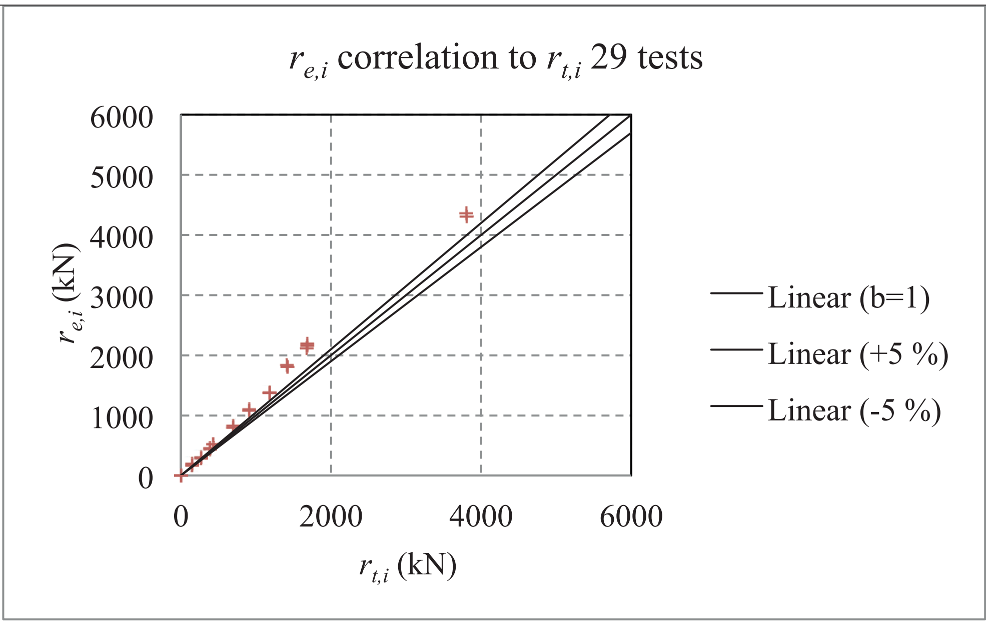


Figure 5. Fitting of data to curve b, b = 1.12.



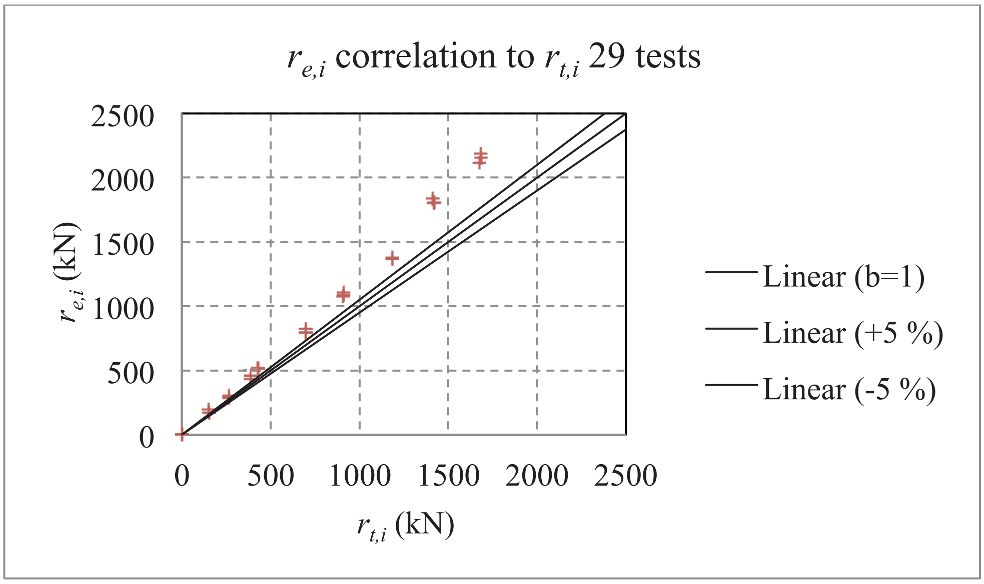


Figure 6. Fitting of data to curve c, b = 1.18.

It can be seen both visually and by observing the value of b, that the fit to curve a is the best. However, due to scatter in the tests, the safety factors based on this data using the Eq. (31) are:

- Curve a: $\gamma_{M1}^* = 1.17$;
- Curve b: $\gamma_{M1}^* = 1.06$;
- Curve c: $\gamma_{M1}^* = 0.98$.

Consider next the evaluation of the results of Table 2 using the groups which are formed based on different slenderness, as in [5]. The groups which are used in this study are:

- Low slenderness: $\bar{\lambda} = 0.48 - 0.71$;
- Medium slenderness: $\bar{\lambda} = 1.00 - 1.50$.

The safety factors using these groups are as follows:

- Curve *a*: $\gamma_{M1}^* = 1.17$;
- **Curve *b*: $\gamma_{M1}^* = 1.05$;**
- Curve *c*: $\gamma_{M1}^* = 0.96$.

As explained above, the safety factor changes for each test. The results using curve *b* and grouping look as given in *Fig.7* with different 29 tests.

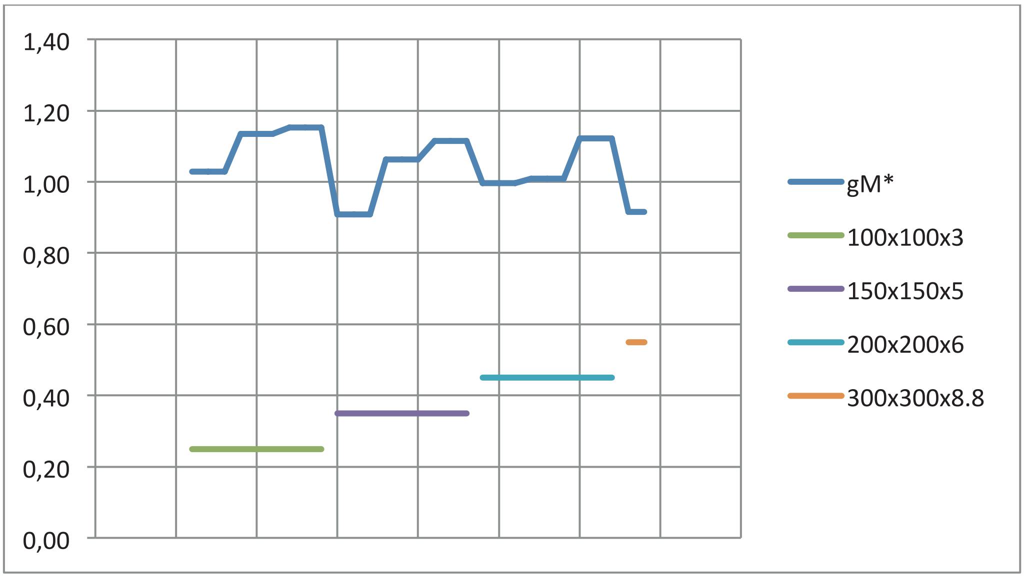


Figure 7. Safety factor for separated tests.

Using this grouping and varying the imperfection factor α the values for the regression coefficient b, coefficient of variation V_δ and safety factor γ_{M1}^* as got, as shown in Table 3.

Table 3. Effect of factor α.

α	0.34	0.35	0.36	0.37	0.38	0.39	0.40	0.41
b	1.09	1.10	1.11	1.11	1.12	1.12	1.13	1.13
V_δ	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
γ_{M1}^*	1.05	1.04	1.03	1.03	1.02	1.01	1.01	1.00

As a conclusion, keeping the design simple without using extra buckling curves and using rounding 1.05 => 1.0, it can stated that the curve *b* is suitable for the hollow sections, provided that the wall thickness of the hollow section is ≥ 3 mm in the range $\bar{\lambda} \leq 1.50$. Figure 8 illustrates the results.

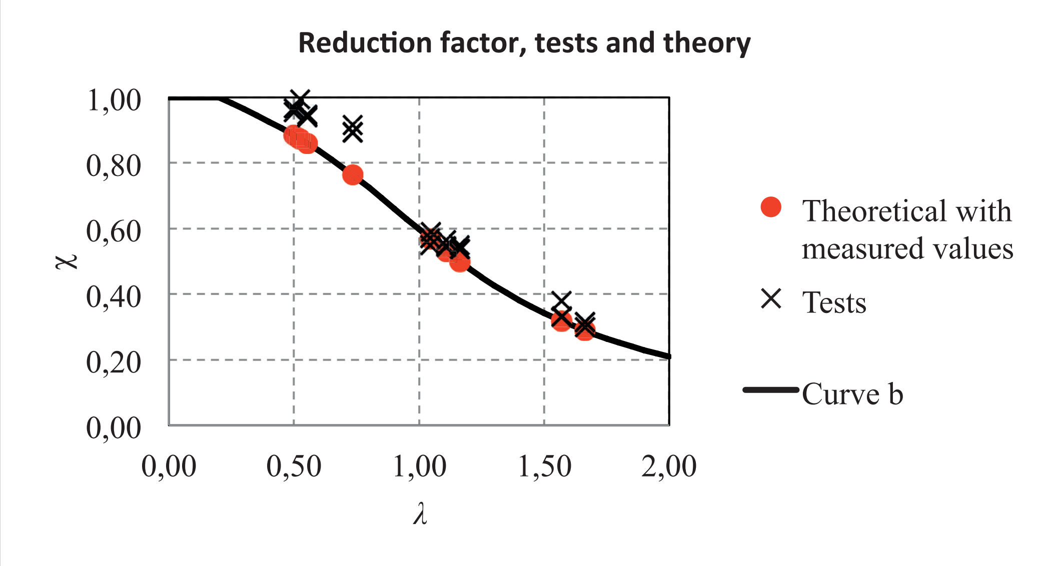


Figure 8. Tests and theory.

Hollow sections 50x50x2

The test results for this hollow section size are given in Table 4.

Table 4. Results for 50x50x2.

Class$_{test}$	*λ_{nom}*	*Test*	*$f_{y,e}$*	*E_e*	*h_e*	*b_e*	*t_e*	*L_{cr}*	*$r_{e,i}$*	*$r_{t,i}$*
-	-	-	*MPa*	*MPa*	*mm*	*mm*	*mm*	*mm*	*kN*	*kN*
PL1-2	0,50	B16_1	522	210000	49,75	49,75	2,02	683	175	177
PL1-2	0,50	B16_2	522	210000	49,75	49,75	1,94	683	173	170
PL1-2	0,50	B16_3	522	210000	49,75	49,75	2,02	682	168	177
PL1-2	1,00	B17_1	522	210000	49,75	49,75	2,02	1366	85	114
PL1-2	1,00	B17_2	522	210000	49,75	49,75	1,94	1365	85	110
PL1-2	1,00	B17_3	522	210000	49,75	49,75	2,02	1365	84	114
PL1-2	1,50	B18_1	522	210000	49,85	49,85	2,02	2051	48	60
PL1-2	1,50	B18_2	522	210000	49,70	49,70	1,94	2049	48	58
PL1-2	1,50	B18_2	522	210000	49,70	49,70	2,02	2049	48	60

The safety factors using this data and grouping as above:

- Curve *a*: $\gamma_{M1}^* = 1.21$;
- Curve *b*: $\gamma_{M1}^* = 1.09$;
- **Curve *c*: $\gamma_{M1}^* = 1.00$**.

Based on this the buckling curve *c* should be used for this case.

Summary

18 column stub tests, 29 buckling tests and 9 tests with 50x50x2 cross-section have been evaluated using EN 1990 Annex D. Tests were completed in LUT during 2014. The column stub tests were evaluated, but the result was that the buckling curve evaluation is the best way to do the analysis. With two cross-sections, 100x100x3 and 200x200x6 the resistance value r_d had to be calculated in the cross-section class 4 but the nominal value $r_{nom,i}$ was calculated in the cross-section class 3. This means increase in the final γ_{M1}^* for these cases, as can be just seen in Fig. 7. However, in the major buckling cases the safety factor 1.05 using the buckling curve *b* was get meaning rounded value 1.00 for buckling. Best fit to the buckling curves was get for the buckling curve *a*, but the scatter in the test results did not show the use of the safety factor 1.0 for the curve *a*. If the resistance value was calculated without reduction due to the cross-section class 4 in these cases, the safety factor was 1.03 with the curve *b*. For the cross-section 50x50x2 the separate evaluation was done due to their test results.

Based on these evaluations the axial resistance of SSAB's double grade hollow sections, which fulfill the requirements of steel grades S355J2H and S420MH, can be defined using the rules of EN 1993-1-1, $f_y = 420$ MPa and

- $t \geq 3$ mm, $\bar{\lambda} \leq 1.50$ => Curve *b* (new rule);
- $t < 3$ mm, => Curve *c* (old rule);

with the factor $\gamma_{M1} = 1.0$.

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[1] EN 1993-1-1. Eurocode 3: design of steel structures – Part 1-1: General rules and rules for buildings. CEN, Brussels, 2005.
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