IDEA StatiCa Member

WP1-1: Comparison of the Buckling Resistance of SHS and RHS Profiles

Project Partner:

IDEA StatiCa

Intermediate Report

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1. Introduction

Objective and Scope

The objective of this report is the verification of the LBA (linear buckling analysis) and GMNIA (**g**eometrically and **m**aterial **n**onlinear **a**nalysis with **i**mperfections) module of the IDEA StatiCa Member software application version 20.1, using as a benchmark the case of the buckling of hot-or cold-finished square and rectangular hollow sections as defined in EN 10210-2 [1] and EN 10219-2 [2]. The resulting resistances from IDEA StatiCa Member are compared with equivalent Abaqus CAE 2019 [3] simulations that were validated in extensive experimental work [4 - 8]. For the recommendation of local and global imperfection assumptions, additional Abaqus simulations were performed. Therefore, the selected imperfections were chosen according to the specifications of EN 1993-1-1 [9], prEN 1993-1-1 [10] and EN 1993-1-5 [11]. Further considerations regarding the choice of eigenmode shapes for interactive cases of global + local buckling were carried out with the aim of creating practice-oriented recommendations. To identify possible application limits two additional cases with significantly higher *c/t* values than in the main study were investigated and again compared with Abaqus simulations. Finally, recommendations are developed for practical design using IDEA StatiCa Member.

2. Model Description

A general FEM-model overview is shown in Fig. 1 and Fig. 2. The IDEA StatiCa Member model consists of three basic parts, the analysed member itself and two additional related members with a far higher stiffness than the actual member. This provides an exclusive failure in the member without the influence of the top and bottom edge boundaries. All settings for the generation of the mesh were set to default. The loads are applied through the boundaries at the top and bottom plate as shown in Fig. 1 in order to create different *N-M* load interactions. Butt welds were selected to achieve fixed boundary conditions of plates of hollow sections to the related members and to avoid any failure of welds prior to failure of the hollow sections.
An equivalent Abaqus comparison model is shown in Fig. 2, where the use was made of three-dimensional shell elements of type S4R. The boundary conditions and additional loads were applied through defined reference points (RF-Points) at the top and the bottom, each connected through an MPC-Beam (multiple point constraint) formulation to associated node sets at the edges. The edges of hollow sections were fixed to these MPC-Beams.

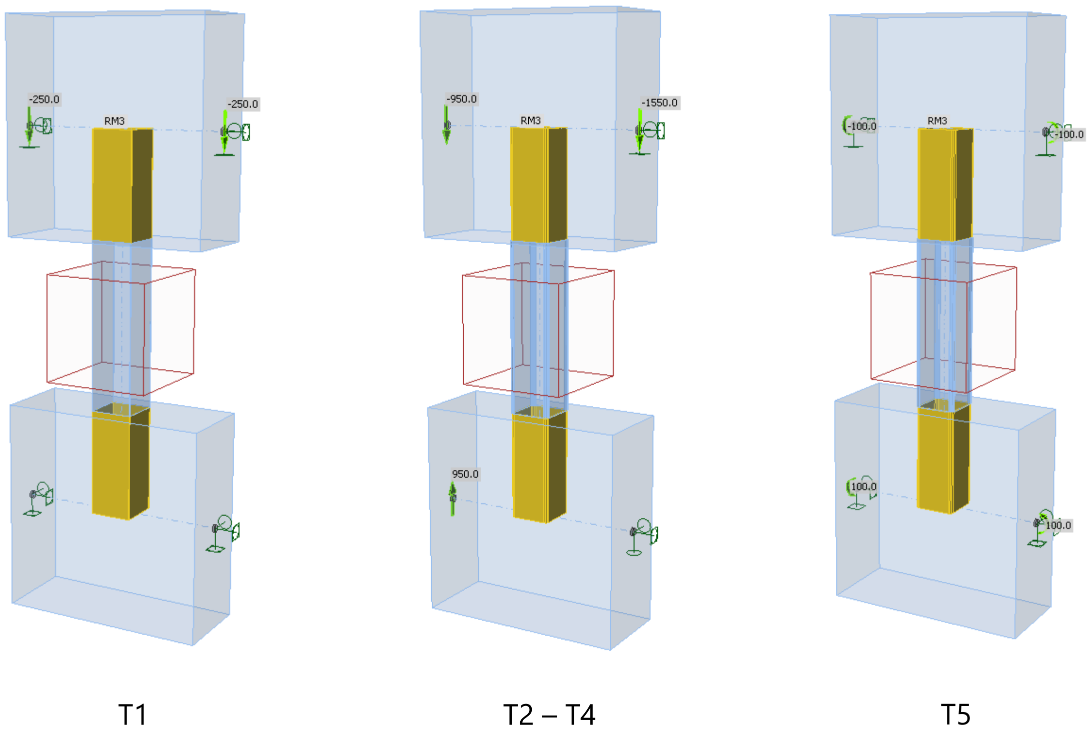


Figure 1: IDEA StatiCa Member transparent model for different load situations T1, T2-T4, T5

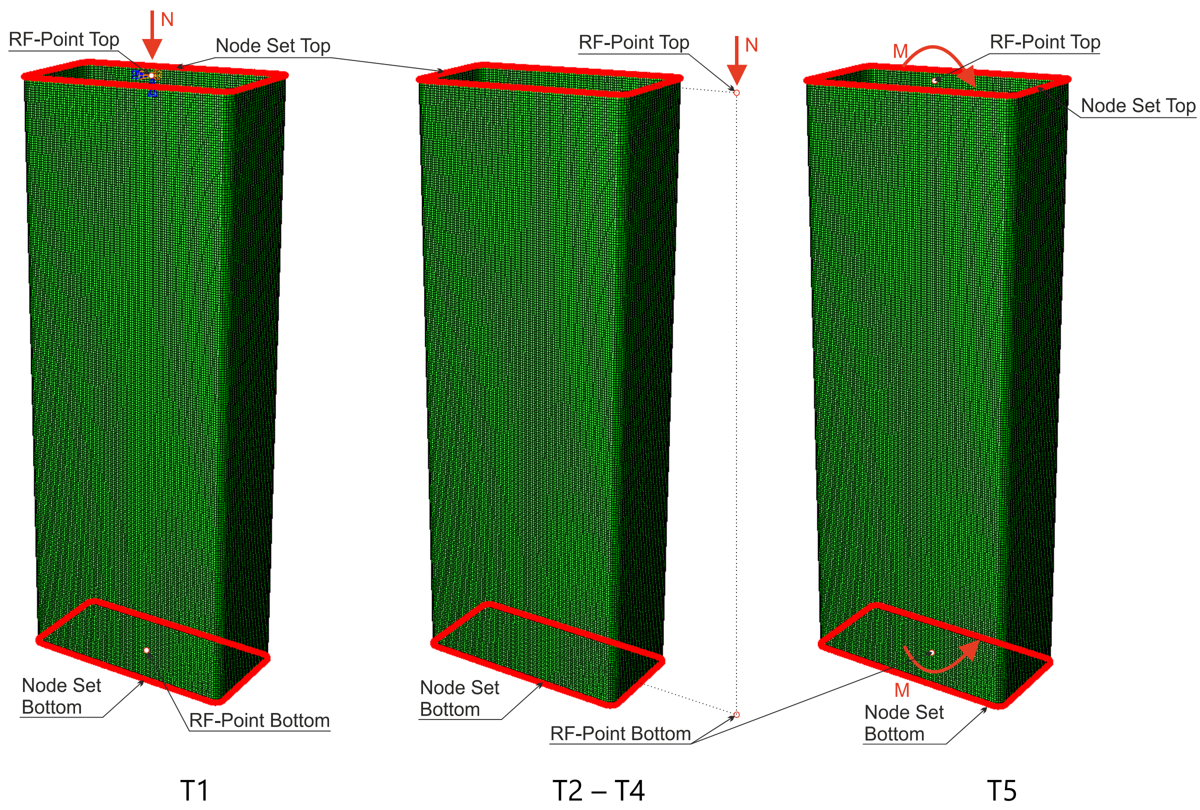
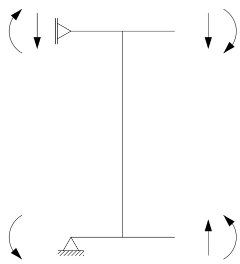
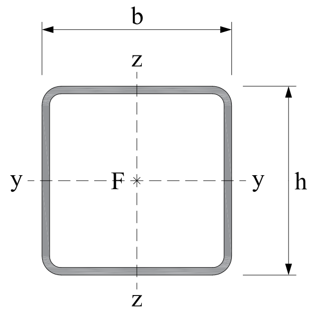
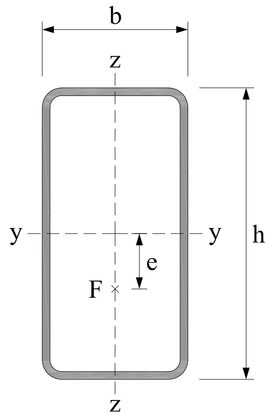


Figure 2: General Abaqus FE-Models for different load situations T1, T2-T4, T5

In total 32 models (see Tab. 1) were compared, regarding different load combinations of normal force and moment (T1 to T5), imperfection amplitudes and cross-section slenderness. The chosen steel grade of S355 and the member length of the considered cross-sections with 800 mm was set constant throughout the investigations. To give a statement about the limits of the IDEA StatiCa Member application, additional models with a far higher *c/t* ratio were considered separately and discussed in section 5.3.2.

Table 1: Parameter overview

				
Considered Cross-Sections	SHS200×5, *c/t* = 37 QS = 4	SHS200×8, *c/t* = 22 QS = 1	RHS300×150×6, *c/t* = 47 / 22 QS=4 / 1	RHS300×150×8, *c/t* = 34.5 / 16.5 QS = 4 / 1
Imperfection amplitude	*B*/200 *B*/400	*B*/200 *B*/400	*B*/200 *B*/400	*B*/200 *B*/400
Load combinations	T1: *N*	T1: *N*	T1: *N*	T1: *N*
	N-M: T2: *e* = 60mm T3: *e* =120 mm T4: *e* = 300mm	*N-M*: T3: *e* = 120mm	*N-M*: T2: *e* = 60mm T4: *e* = 300mm	*N-M*: T2: *e* = 60mm T4: *e* = 300mm
	T5: *M*	T5: *M*	T5: *M*	T5: *M*

3. Validation of the Abaqus model

The Abaqus model used throughout this report was validated through an extensive analytical, numerical and experimental campaign over the course of the RFCS project HOLLOSSTAB. The reader is referred to the references of the project for the details [4-8]. A short description of the model is given here:

- Isoparametric shell elements with reduced integration of type S4R are used, with a mesh density of 60 elements in circumferential and (depending on the total member length) 100 elements per meter in longitudinal direction.

- In order to have compatibility with the IDEA StatiCa Member model, an elastic-ideal plastic material model was used, with an infinite yield plateau assumed at $\sigma_{von\text{-}Mises}=f_y$.
- Imperfection amplitudes based on eigenmodes and with various amplitudes (see the following sections) were considered.
- The load introduction and boundary conditions make use of a Multi-Point Constraint (MPC) type of constraints at the member ends, which implies a rigid connections between the nodes at the extremity and a reference node at the centroid of the respective sections.

4. Choice of imperfections

4.1. Local imperfections

According to EN 1993-1-5, Annex C [11] the magnitude of local imperfections for the analysis of plate buckling may be assumed with a value of e_0 = *B/*200, where *B* is the smaller of the two corresponding dimensions of a rectangular hollow section. Nevertheless, referring to the findings of Rusch and Lindner [12] as well as Toffolon and Taras [5] a determined amplitude of *B/*400 was found to be more suitable to represent the design curve for local buckling ("Winter curve") of EN 1993-1-5 [11] in numerical calculations. To underpin this statement, several GMNIA calculations were performed for a centrically loaded cold-formed and hot-rolled SHS200 profile with a varying thickness and a constant length of 800 mm to ensure local buckling exclusively. The associated imperfection range varied between the upper bonds of *B/*200 and *B/*400 and an additional imperfection of *B/*300 in between.

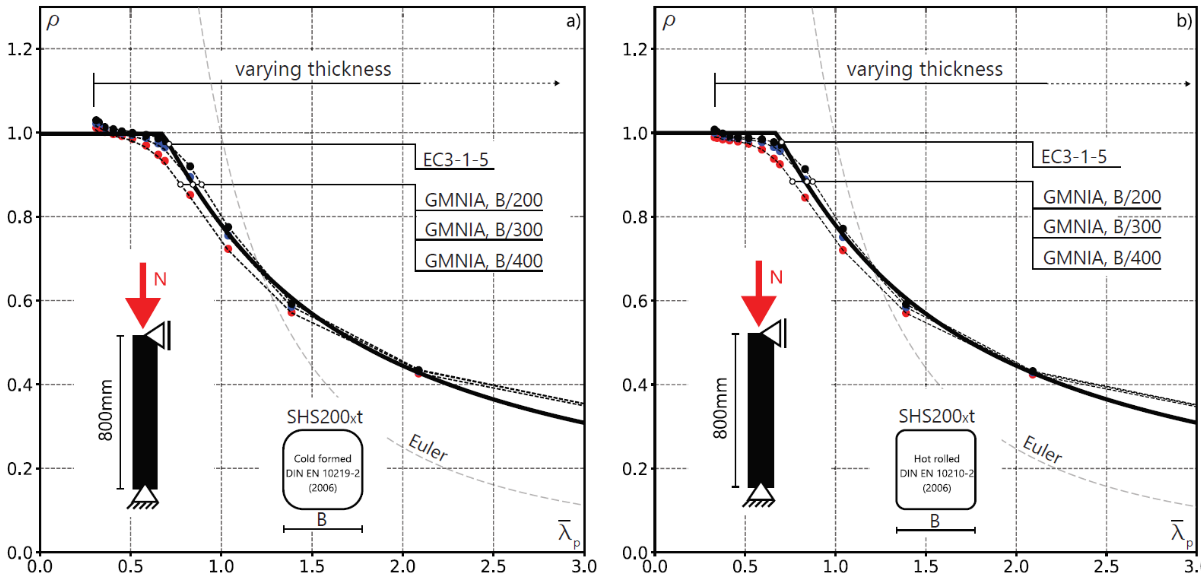


Figure 3: GMNIA calculations for an SHS200 profile and comparison with code provision of EN 1993-1-5 [11] a) cold-formed; b) hot-rolled

A summary of the GMNIA calculations for the hot-finished [1] as well as cold-formed [2] SHS200 profile is illustrated in Fig. 3. For the calculations with the imperfection amplitude of *B/*200, values are obtained which are comparatively conservative lying below the local buckling curve of EN 1993-1-5 [11]. On the other hand, the results of the calculations based on the imperfection amplitude of *B/*400 show a better agreement with the local buckling curve and confirms the observations by [5] and [12].

4.2. Global Imperfections

The general preselection of the initial imperfection magnitude depends on different factors like: (i) the type of analysis according to the considered cross-section failure linked to the cross-section class, (ii) the type of imperfection considered for further calculations i.e. geometric imperfections only or equivalent imperfections including a geometric bow imperfection and additional residual stresses, (iii) the benchmark resistance in term of a plastic or elastic calculation which specify the choice of imperfection. The latter corresponds to the global buckling concept of EN 1993-1-1 [9] where a cross-section dependent imperfection factor α takes both into account.

According to EN 1993-1-1 [9] and prEN 1993-1-1 [10] the bow imperfection amplitude e_0 can be determined using two approaches, considering either a tabulated length proportional value or a slenderness-based formulation based on the elastic critical buckling modes. According to EN 1993-1-1, Table 5.1 [9] e_0 is the ratio between the member length and a value that depends on the global buckling curve (a_0, a, b, c, d) and the analysis type: elastic or plastic. A summary of GMNIA calculation is presented in Fig. 4, again for an SHS200 profile with the geometric predefinitions of cold-formed and hot-rolled steel, a varying length and a constant thickness of 12.5 mm to exclude local buckling effects.

In the current draft of prEN 1993-1-1 [10], a modified formulation for the determination of the length affine imperfection e_0 is presented (see Eq. 1). Where α is the imperfection factor, depending on the relevant buckling curve, ε the material parameter considering the steel grade, β the reference bow imperfection and L the member length. The values for buckling about *y-y* axis were used for hollow section columns. Associated GMNIA calculations are summarized in Fig. 5.

$$e_0 = \frac{\alpha}{\varepsilon} \cdot \beta \cdot L \tag{1}$$

Table 2: Reference bow imperfection β [10]

Buckling about axis	Elastic design	Plastic design
y-y	1/110	1/75
z-z	1/200	1/68

The back-calculation of slenderness-based equivalent bow imperfections, in both EN 1993-1-1 [9] and prEN 1993-1-1 [10], is provided by Eq. 2.

$$e_0 = \alpha \cdot \left(\bar{\lambda} - 0.2\right) \frac{M_{Rk}}{N_{Rk}} \tag{2}$$

Where e_0 is the target imperfection, α the imperfection factor for the relevant buckling curve, $\bar{\lambda}$ the member relative slenderness, M_{Rk} the characteristic moment resistance of the critical cross-section and N_{Rk} the characteristic axial resistance of the cross-section. The imperfection amplitudes calculated this way result in smaller deflections and thus resistances that are closer to the buckling curves. Fig. 6 gives an overview of GMNIA calculations based on the elastic (Fig. 6 a, b) and plastic (Fig. 6 c, d) resistance. The latter leads to results that are slightly on the safe side below the global buckling curves. In terms of practical usability, the length affine approach requires fewer computationally intensive steps – calculation of the slenderness, which requires the determination of the critical buckling load and the cross-section resistance – and is therefore simpler in its application.

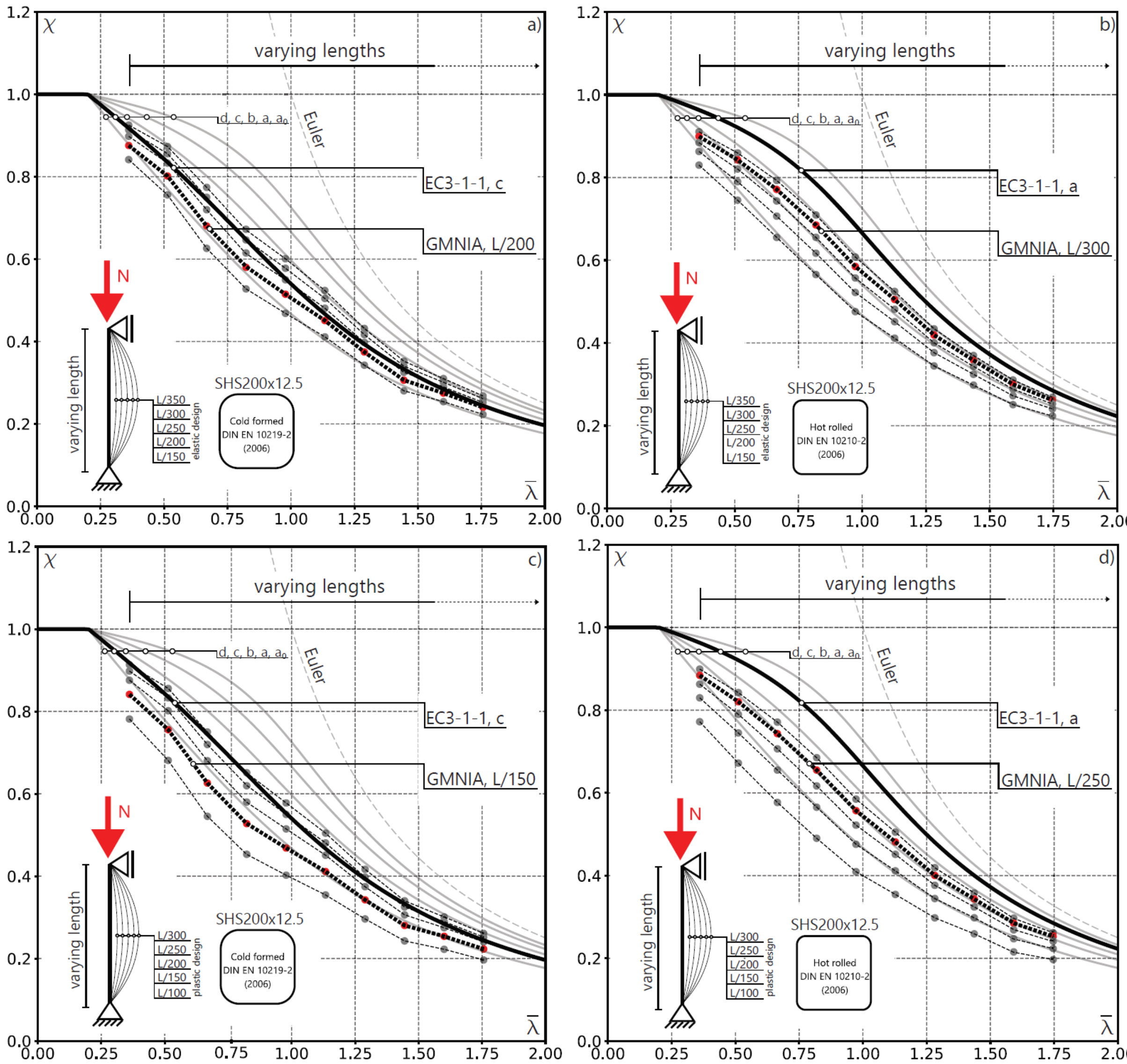


Figure 4: Length affine [9] GMNIA calculations for an SHS200×12.5 profile and comparison with code provision of EN 1993-1-1 [9] a) cold-formed elastic design; b) hot-rolled elastic design, c) cold-formed plastic design, d) hot-rolled plastic design

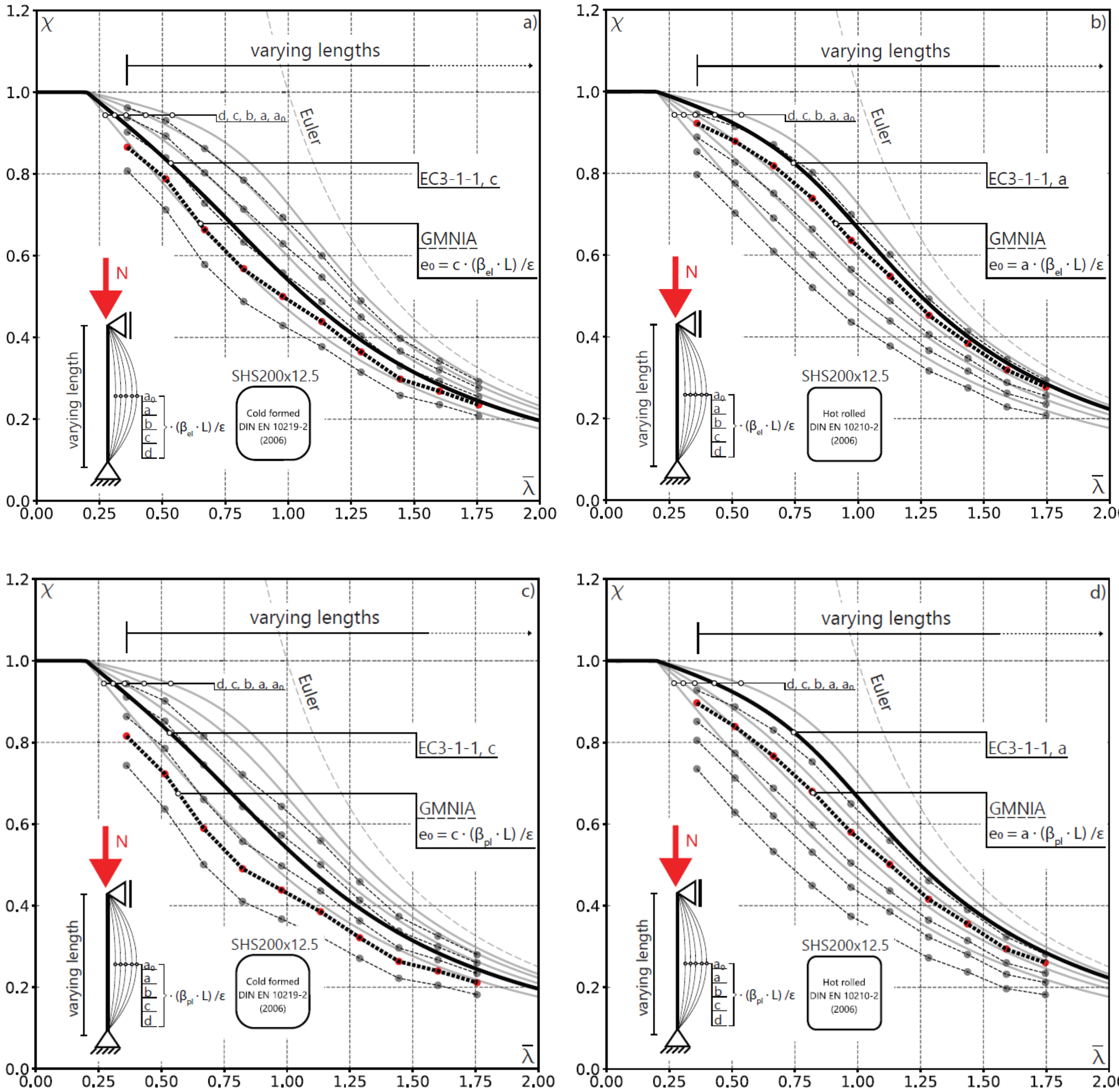


Figure 5: Length affine [10] GMNIA calculations for an SHS200×12.5 profile and comparison with code provision of EN 1993-1-1 [2] a) cold-formed elastic design; b) hot-rolled elastic design; c) cold-formed plastic design; d) hot-rolled plastic design

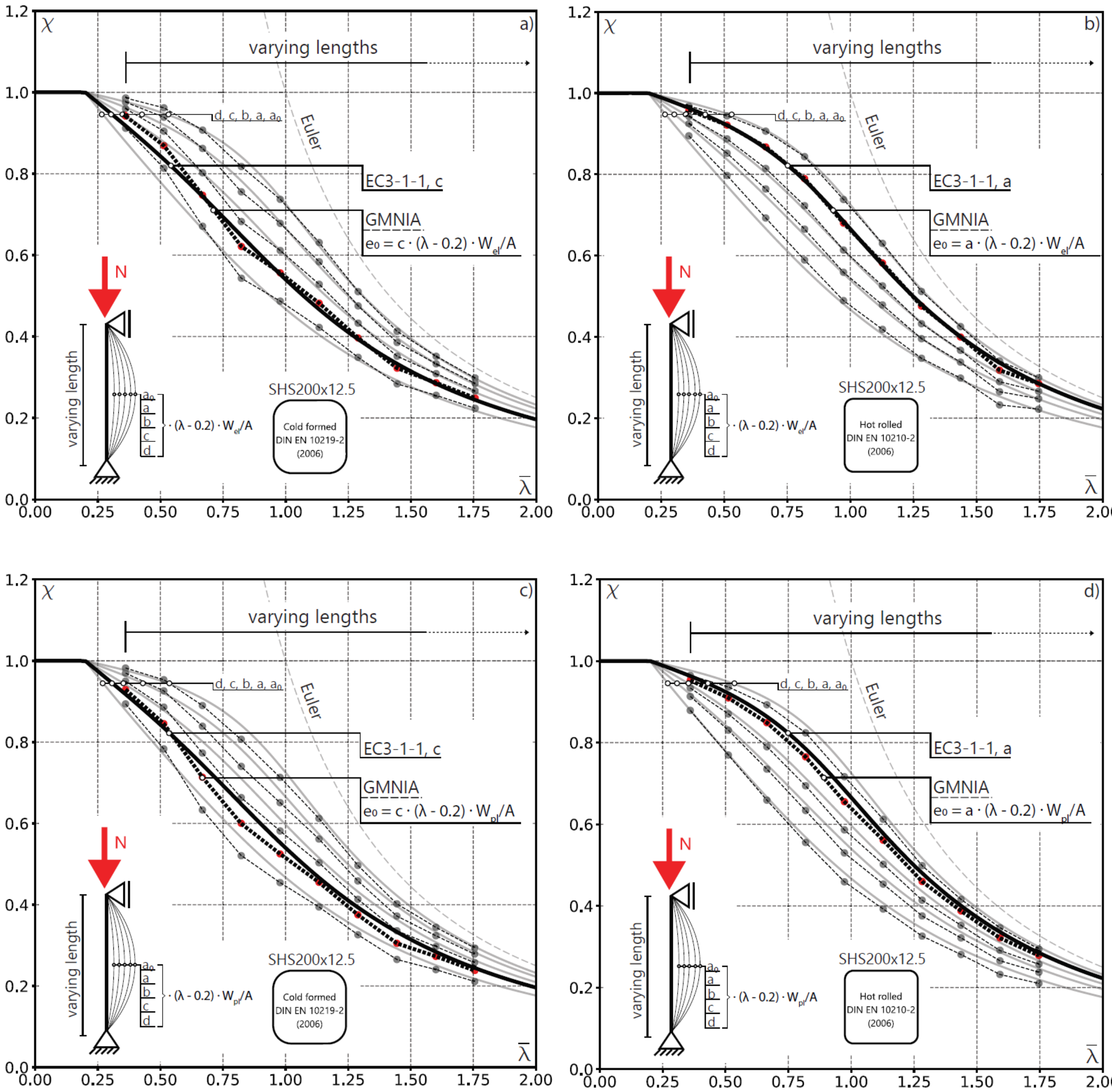


Figure 6: Slenderness affine [9] GMNIA calculations for an SHS200×12.5 profile and comparison with code provision of EN 1993-1-1 [9] a) cold-formed elastic design; b) hot-rolled elastic design; c) cold-formed plastic design; d) hot-rolled plastic design

Based on the calculations in Fig. 4 a length affine approach according to EN 1993-1-1 [9] is sufficient and safe sided by taking the elastic design approach for the evaluation of the imperfection amplitude. The same assumption (elastic design) applies for the new formulation of the imperfection amplitude (see Eq. 1) according to prEN 1993-1-1 [10]. A summary of the calculations can be taken from Fig. 5.

For the slenderness affine imperfection amplitude approach, on the other hand, the use of plastic resistance is recommended. This approach requires that the magnitude of the relative slenderness is determined beforehand.

5. Comparisons and Recommendations

5.1. Comparison of the LBA Results:

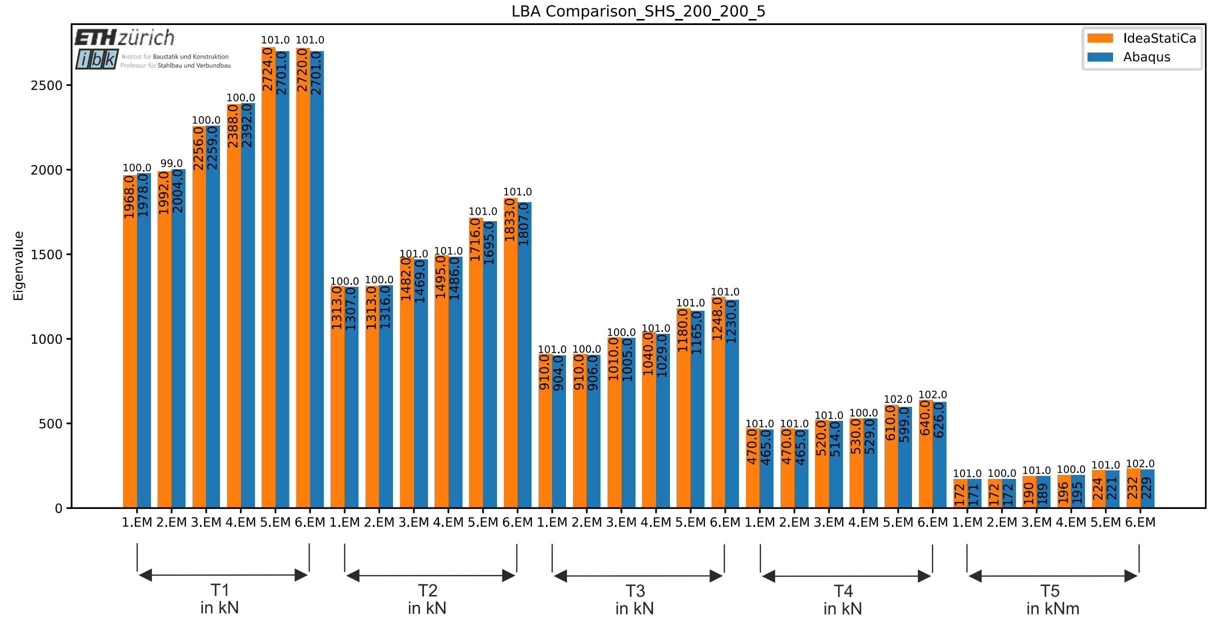
Table 3: LBA Results – SHS Profiles

	Eigenvalue (EV)					
	EV1	EV 2	EV 3	EV 4	EV 5	EV 6
SHS200×200×5						
T1 in [kN]						
IDEA StatiCa	1968.00	1992.00	2256.00	2388.00	2724.00	2720.00
Abaqus	1977.52	2004.07	2258.56	2391.88	2701.41	2701.42
Comparison	1.00	0.99	1.00	1.00	1.01	1.01
T2 in [kN]						
IDEA StatiCa	1313.00	1313.00	1482.00	1495.00	1716.00	1833.00
Abaqus	1307.49	1315.53	1468.83	1485.97	1695.19	1807.07
Comparison	1.00	1.00	1.01	1.01	1.01	1.01
T3 in [kN]						
IDEA StatiCa	910.00	910.00	1010.00	1040.00	1180.00	1248.00
Abaqus	904.50	906.30	1005.36	1029.20	1165.24	1230.07
Comparison	1.01	1.00	1.00	1.01	1.01	1.01
T4 in [kN]						
IDEA StatiCa	470.00	470.00	520.00	530.00	610.00	640.00
Abaqus	464.99	465.46	513.99	529.41	598.76	625.95
Comparison	1.01	1.01	1.01	1.00	1.02	1.02
T5 in [kNm]						
IDEA StatiCa	172.00	172.00	190.00	196.00	223.86	232.44
Abaqus	171.13	171.67	188.76	195.03	220.94	228.99
Comparison	1.01	1.00	1.01	1.00	1.01	1.02
SHS200×200×8						
T1 in [kN]						
IDEA StatiCa	7950.00	8070.00	9120.00	9630.00	11220.00	11220.00
Abaqus	8011.72	8131.52	9139.27	9599.50	11015.60	11015.60
Comparison	0.99	0.99	1.00	1.00	1.02	1.02
T3 in [kN]						
IDEA StatiCa	3660.00	3660.00	4080.00	4170.00	4710.00	4950.00
Abaqus	3645.85	3648.20	4021.24	4132.10	4661.06	4857.85
Comparison	1.00	1.00	1.01	1.01	1.01	1.02
T5 in [kNm]						
IDEA StatiCa	690.00	694.00	760.00	784.00	892.00	912.00
Abaqus	684.24	687.93	751.24	775.56	881.04	897.83
Comparison	1.01	1.01	1.01	1.01	1.01	1.02

Table 4: LBA Results - RHS Profiles

	Eigenvalue (EV)					
	EV1	EV2	EV3	EV4	EV5	EV6
RHS300×150×6						
T1 in [kN]						
IDEA StatiCa	2280.00	2370.00	2610.00	2640.00	2880.00	3030.00
Abaqus	2264.58	2354.49	2576.72	2614.35	2845.40	2978.12
Comparison	1.01	1.01	1.01	1.01	1.01	1.02
T2 in [kN]						
IDEA StatiCa	2200.00	2300.00	2575.00	2600.00	2775.00	2850.00
Abaqus	2196.77	2274.87	2525.94	2553.15	2749.18	2822.15
Comparison	1.00	1.01	1.02	1.02	1.01	1.01
T4 in [kN]						
IDEA StatiCa	1475.00	1475.00	1650.00	1700.00	1875.00	1900.00
Abaqus	1456.45	1457.18	1628.21	1665.77	1845.14	1862.70
Comparison	1.01	1.01	1.01	1.02	1.02	1.02
T5 in [kNm]						
IDEA StatiCa	680.00	680.00	732.00	736.00	820.00	824.00
Abaqus	662.55	663.49	707.84	710.68	779.25	792.19
Comparison	1.03	1.02	1.03	1.04	1.05	1.04
RHS300×150×8						
T1 in [kN]						
IDEA StatiCa	5370.00	5580.00	6240.00	6300.00	6780.00	7080.00
Abaqus	5344.15	5551.39	6105.70	6171.92	6726.64	6970.50
Comparison	1.00	1.01	1.02	1.02	1.01	1.02
T2 in [kN]						
IDEA StatiCa	5200.00	5375.00	6125.00	6150.00	6550.00	6700.00
Abaqus	5179.70	5355.54	5979.81	6022.95	6490.38	6597.12
Comparison	1.00	1.00	1.02	1.02	1.01	1.02
T4 in [kN]						
IDEA StatiCa	3425.00	3425.00	3875.00	3975.00	4425.00	4475.00
Abaqus	3401.56	3407.55	3797.93	3881.81	4324.90	4358.42
Comparison	1.01	1.01	1.02	1.02	1.02	1.03
T5 in [kNm]						
IDEA StatiCa	1587.00	1590.00	1707.00	1722.00	1905.00	1920.00
Abaqus	1544.95	1546.96	1648.31	1653.59	1807.97	1837.18
Comparison	1.03	1.03	1.04	1.04	1.05	1.05

The LBA comparison generally shows small deviations between the results of IDEA StatiCa Member and Abaqus for the six considered eigenvalues (EV1 – EV6), especially for load case T1 to T3 with a maximum difference of 2%. Slightly higher deviations are determined for load case T4 and T5 with a maximum difference of 5%. This level of deviation between bifurcation loads is common and well within the range of acceptability. IDEA StatiCa Member always provides slightly higher linear buckling factors than Abaqus.



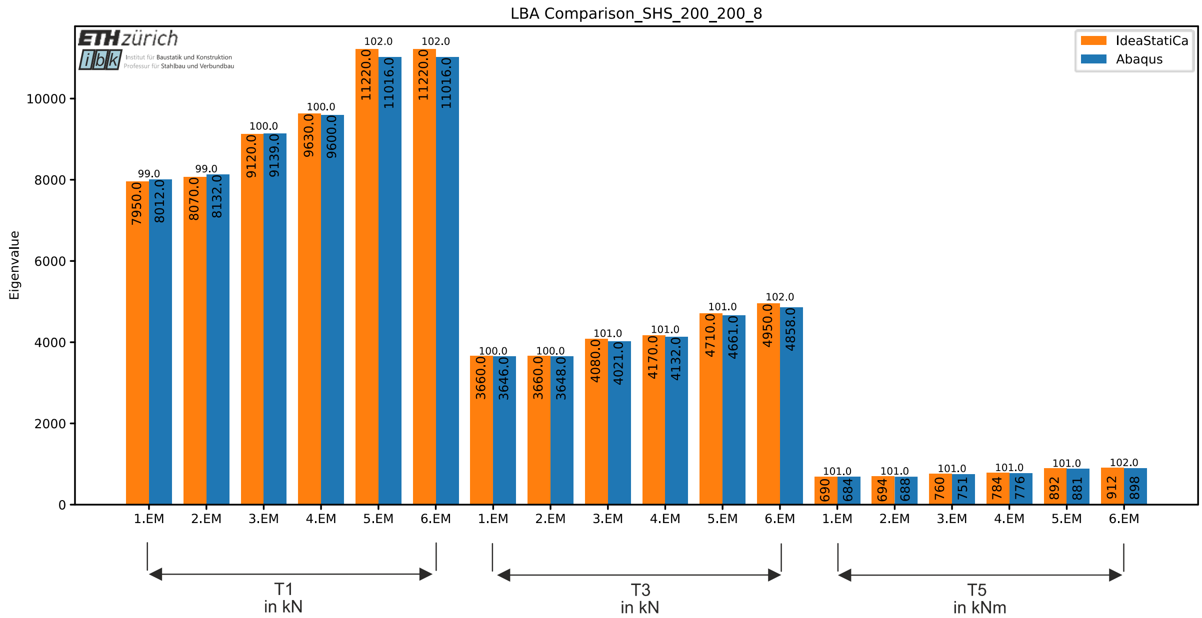
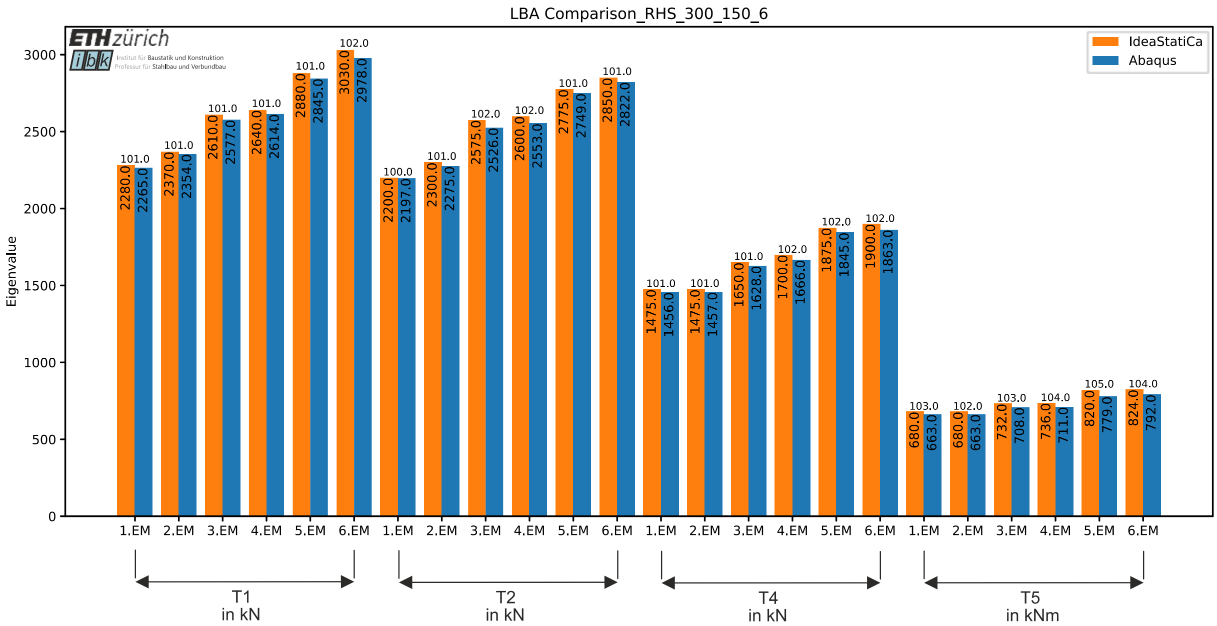


Figure 7: Comparison of LBA results for SHS200×200×5 and SHS200×200×8



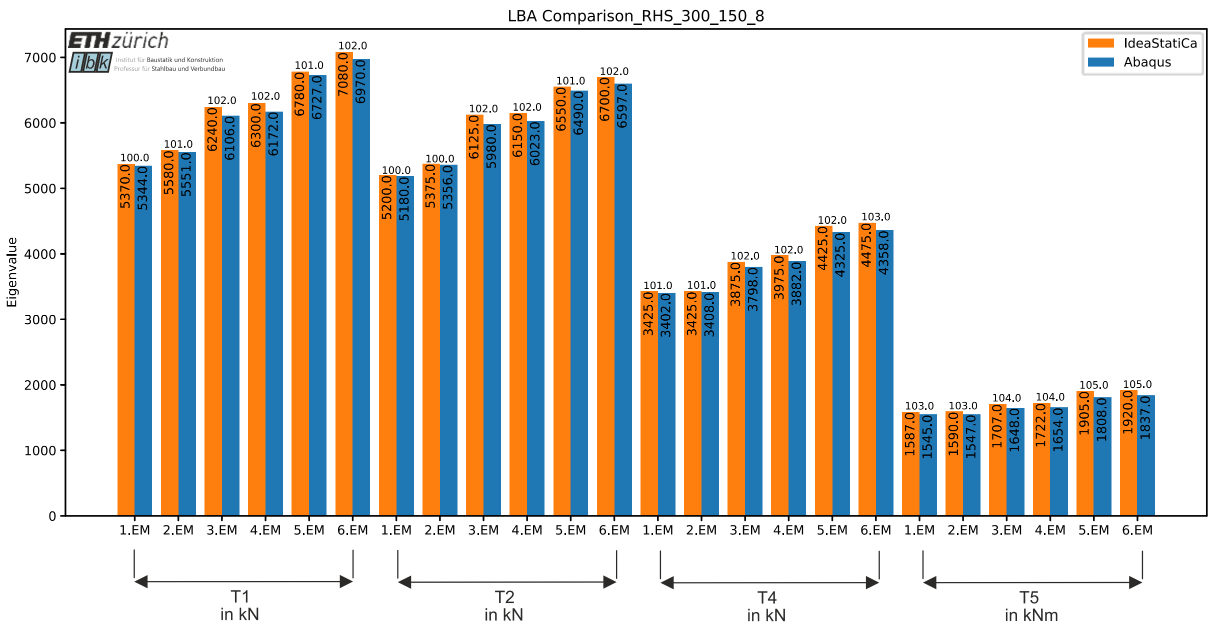
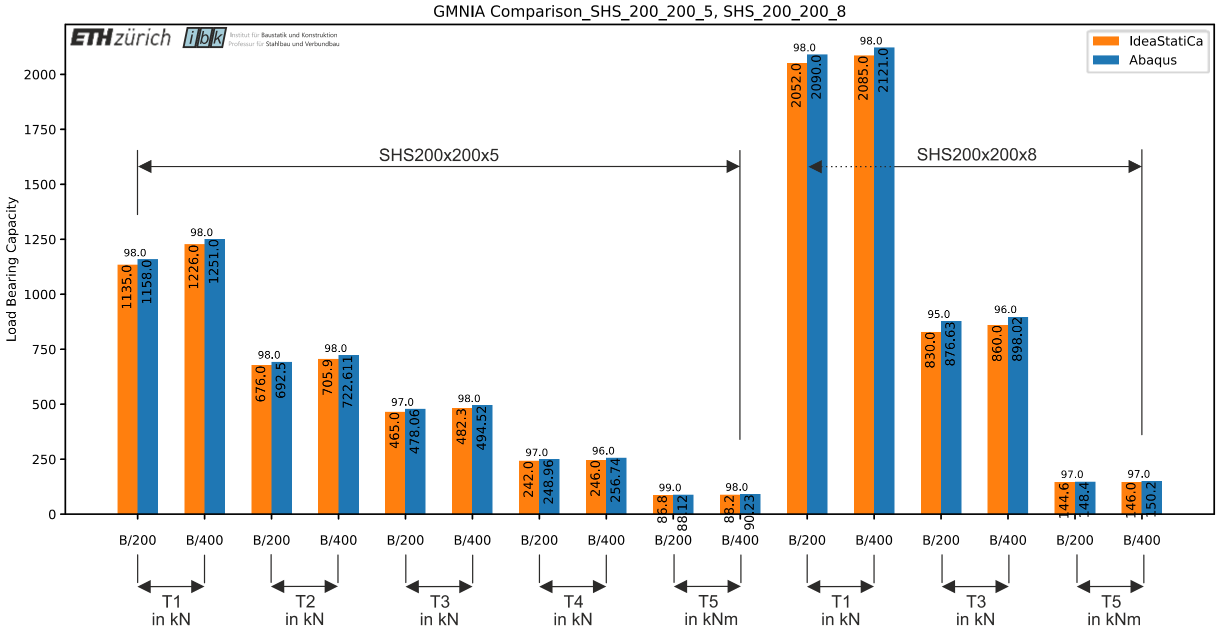


Figure 8: Comparison of LBA results for RHS300×150×6 and RHS300×150×8

5.2. Comparison of the GMNIA Results:



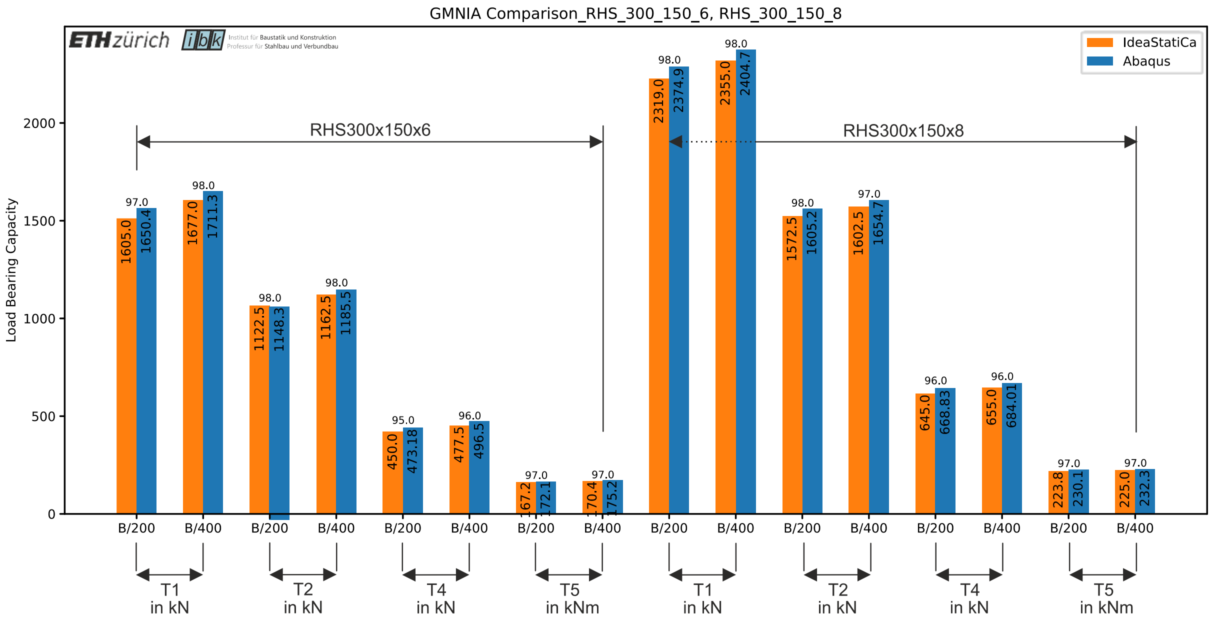


Figure 9: Summary of the GMNIA Results

The GMNIA comparison between IDEA StatiCa Member and Abaqus generally shows only minor deviations of the achieved maximum loads. The smallest deviations occur for the load cases T1 and T2 with a maximum of 3%, rising with a higher eccentricity up to 5% in individual cases. The achieved loads, calculated by IDEA StatiCa Member are always slightly lower than the calculated loads in Abaqus. Again, this level of deviation is common and well between the range of acceptability.

5.3. Additional Remarks and Application Notes

5.3.1. Eigenform mismatch

In some individual cases, a mismatch of the eigenforms was identified as shown for the combined load situation (T4, e = 300 mm) of the RHS300×150×6 Profile (see Tab. 5). If the results of the first two eigenvalues in IDEA StatiCa Member are identical, the eigenform of the LBA may be swapped: the first shown eigenform is actually the second one and vice versa. This can lead in a further GMNIA calculation to a result representing an ultimate load bearing capacity that is actually too high. Therefore, an additional GMNIA check should be performed choosing the second eigenform from the LBA calculation. Subsequently the two performed GMNIA calculations have to be compared, choosing the lower value for further design checks.

Table 5: RHS300×150×6, T4 – Swapped eigenvalue

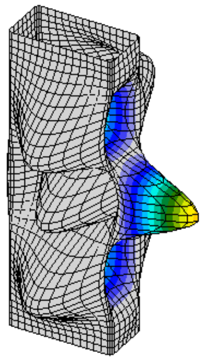
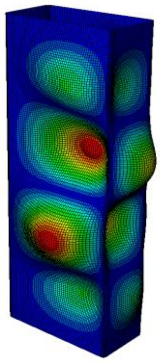
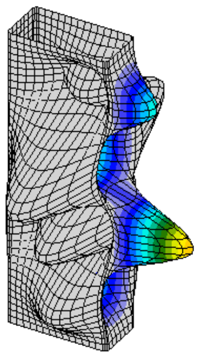
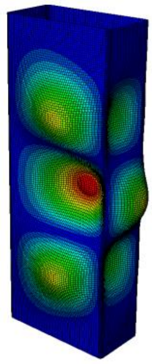
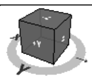
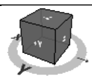
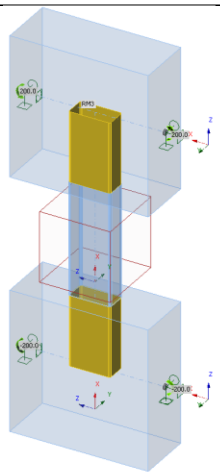
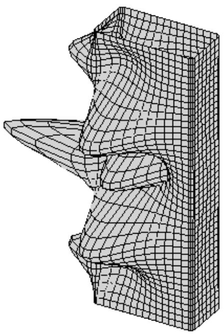
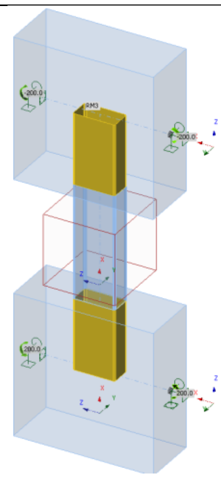
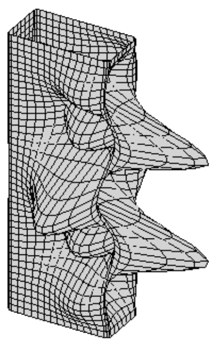
1st Eigenmode		2nd Eigenmode	
IDEA StatiCa	Abaqus	IDEA StatiCa	Abaqus
			

Table 6: RHS300×150×6, T5 – Different direction of the imperfection amplitude

For the sake of completeness, although of secondary importance for the determined maximum load, it should be pointed out that the direction of the imperfection amplitude can change depending on the direction of the load (see Tab. 5). If necessary, the direction of the imperfection amplitude can be changed by changing the sign in the default settings of the GMNIA calculation.

5.3.1. Choice of eigenmode shapes for interactive cases of global + local buckling

The strength predictions based on GMNIA calculations can be strongly dependent on the choice of imperfection shapes, which are determined in advance by LBA analysis and the respective associated imperfection amplitudes. A common approach is to use the shape of the first eigenmode as the applied initial imperfection for subsequent GMNIA calculations. However, in important cases, this approach could neglect a possible interaction between local and global buckling, with significant consequences for the estimated load bearing capacity. For this reason, it is important to assure that *both* local and global imperfection shapes are included in the GMNIA calculations, whenever an interaction between the two is detrimental. On the other hand, it may be both unnecessary and cumbersome to *always* consider both types of imperfection. For this reason, recommendations are developed in the following section, based on examples and previous experience of the authors.

In the Abaqus calculations carried out for this purpose and summarized in Fig.10 the effects of the local and global imperfection amplitudes were set to constant size-proportional values of *B/*400 and *L/*1000, repectively. This choice of imperfection amplitudes allows a realistic consideration of the local buckling behaviour exclusively (*B/*400) and the effects of additional possible global imperfections leading to a mixed imperfection mode (*B/*400 + *L/*1000). In these calculations, the length proportional value for the global imperfection amplitude *L/*1000 was set lower than the recommendations of EN 1993-1-1, Table 5.1 [9], based on the specifications of DIN EN 1090-2 [13]. For thicker-walled sections, this leads to a good approximation of the buckling curve "a" valid for hot-finished sections.

Fig. 10 a and b show the results of GMNIA calculation for a centrically loaded hot-rolled SHS200×8 and an SHS200×5 of steel grade S355 profile with varying member lengths from 500 mm to 4500 mm and 1000 mm to 7500 mm, respectively. Three different sets of GMNIA calculations were performed in order to obtain the load bearing capacity using only the local eigenform (red dots), a combination of the local and global eigenforms (blue dots) and the global eigenform exclusively (green dots). The local capacity (red dots) is represented through the local slenderness and therefore remains almost at the same spot for different lengths, forming a transition line for the "dominant" first eigenform. Therefore, all models with a calculated $\alpha_{cr,glob} < \alpha_{cr,loc}$ will have a first eigenmode governed by global buckling, while all models with $\alpha_{cr,glob} > \alpha_{cr,loc}$ have a local first eigenmode. The global capacity (green and blue dots), on the other hand, is represented through the global slenderness as defined for the buckling curves of EN 1993-1-1 [9].

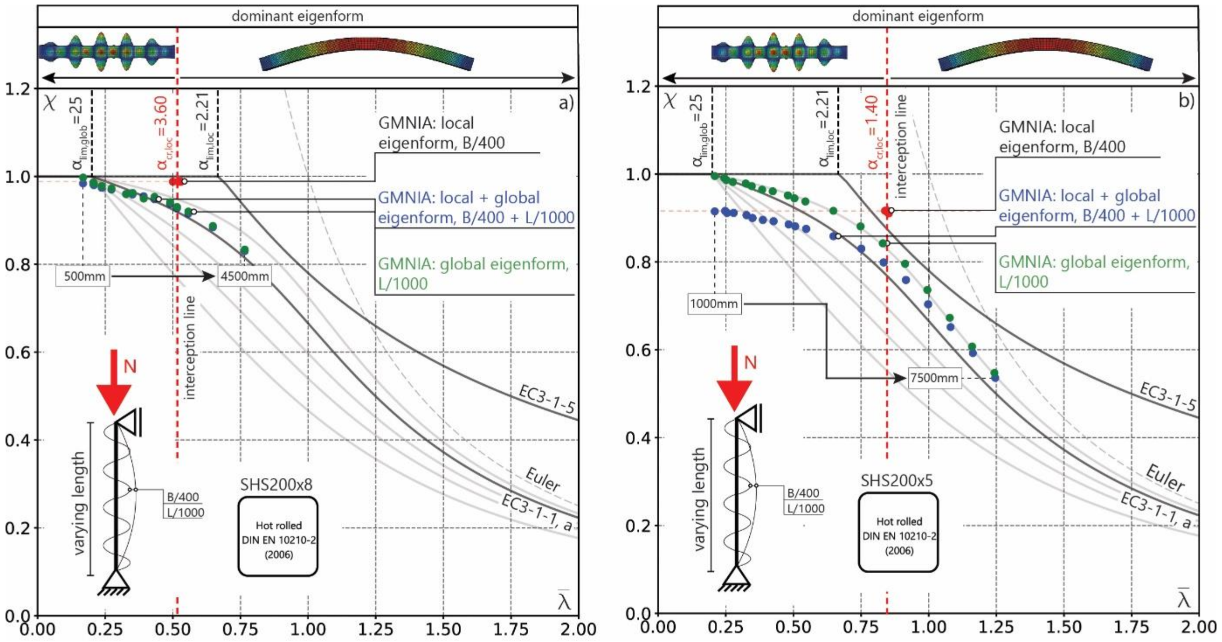


Figure 10: Impact of the choice and combination of the eigenforms on the buckling resistance a) SHS200×8; b) SHS200×5

Fig. 10 a shows the results for a hot-rolled SHS200×8 profile. The corresponding $\alpha_{cr,loc}$ = 3.60 lies between the global and local limit values of $\alpha_{lim,glob}$ = 25 and $\alpha_{lim,loc}$ = 2.20, derived respectively from the plateau values of the column buckling curves in EN 1993-1-1 [9] and the "Winter curve" for plate buckling (case of constant compression in a plate supported on all four sides). Due to the fact that $\alpha_{cr,loc} > \alpha_{lim,loc}$ local effects do not have a significant influence on the overall behaviour of this thicker-walled section. This is confirmed by comparing the GMNIA results of the global capacity, using the overlaid global and local eigenforms and the GMNIA results using the global eigenform only, leading to a maximum difference of 1.5% and the conclusion that local imperfections have a subordinate influence for the considered cross-section. On the other hand, local imperfections generally need to be taken into account in cases where $\alpha_{cr,loc} < \alpha_{lim,loc}$, see Fig. 10 b. Comparing the GMNIA results of the global capacity again, taking the superposition of global and local eigenmode as opposed to only the global eigenmode, will lead to significant differences. Neglecting the inclusion of local imperfections, would lead to an overestimation of the maximum load by up to 8%, especially for shorter members. On the other hand, for shorter members it may be convenient and suitable to only account for local buckling in GMNIA design calculations.

The requirement to apply – or not – global imperfections may be formulated depending on the value of $\alpha_{cr,glob}$ and its ratio to $\alpha_{cr,loc}$, denominated as "*f*" in the following (see Eq. 3).

$$f = \frac{\alpha_{cr,glob}}{\alpha_{cr,loc}} = \frac{\lambda_{loc}^2}{\lambda_{glob}^2} \tag{3}$$

One obvious limit case for which it is certainly appropriate to neglect the global imperfections is given for cases where $\alpha_{cr,glob} \geq \alpha_{lim,glob}$ is fulfilled. This would be equivalent to a case where the compression member is so stocky that it comes to lie in the "plateau" of the global buckling

curves of EN 1993-1-1 [9]. If the upper condition is not met, the relation described by factor *f* (see Eq. 3) may be checked and a limit factor may be used to ensure that, if the distance between the two α_{cr}-values is high enough, the influence of global imperfections is small enough to be neglected. In these cases, GMNIA calculations may be performed considering only local imperfections, as these will determine the resistance entirely.
Based on experience and the theoretical considerations of the analytical buckling curves and their relative distance, it was possible to formulate the following, safe-sided recommendations. Therefore, whenever it becomes necessary to include local imperfections in GMNIA calculations (cases with $\alpha_{cr,loc} < \alpha_{lim,loc}$), the simultaneous consideration of global imperfections may be neglected if factors *f* exceed the following limit values (valid for square and rectangular hollow sections):

- $f_{lim,a}$ = 3.50 for hot-finished SHS and RHS for which buckling curve a applies
- $f_{lim,c}$ = 6.00 for cold-formed SHS and RHS for which buckling curve c applies

The flowchart below provides a practice-oriented overview of the above-described decision criteria. The values of $\alpha_{lim,loc}$ and $\alpha_{lim,glob}$ are 2.2 and 25, respectively.

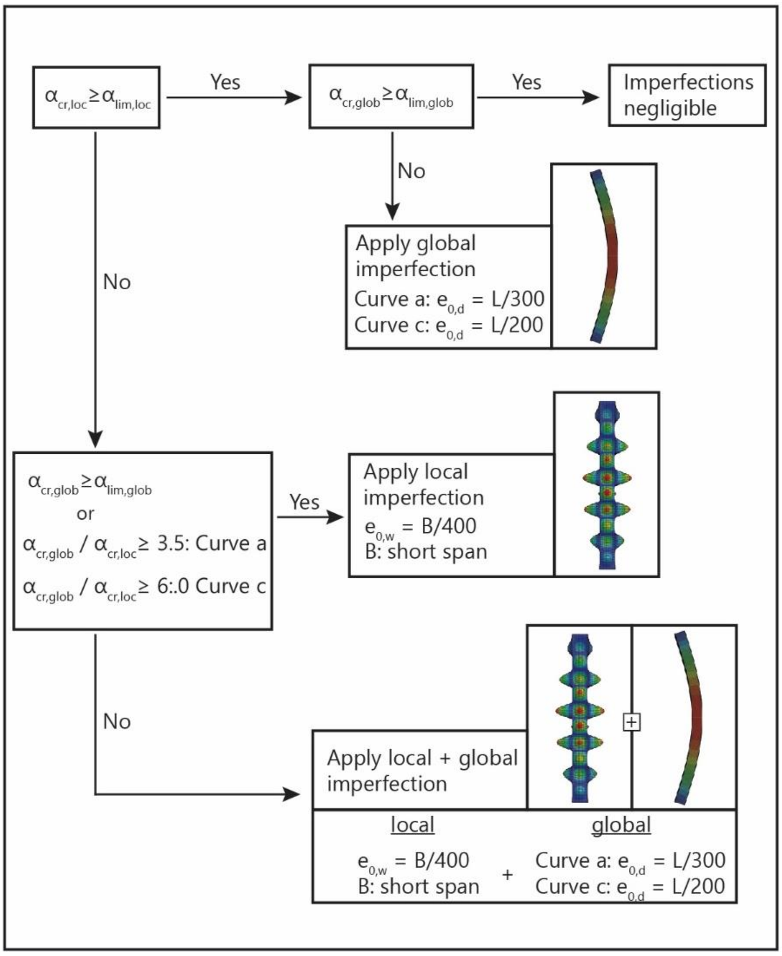


Figure 11: Flowchart in order to determine the applied imperfections

5.3.2. Application limits

Two additional models of the same outer dimensons as shown in Tab. 1, but with a far higher *c/t* values were used to investigate selectively possible limits of the application for the load case of pure compression and pure bending (see Tab. 7).

Table 7: Model overview

Considered Cross-Sections	SHS200×200×1, S355, c/t = 196	RHS300×150×1, S355, c/t = 146
Imperfection amplitude	$B/400$	$B/400$
Load combinations	N	M

Table 8: LBA comparison – SHS200×200×1, N

LBA – N						
	EV1 in [kN]	EV2 in [kN]	EV3 in [kN]	EV4 in [kN]	EV5 in [kN]	EV6 in [kN]
Abaqus	16.02	16.20	18.33	19.50	21.46	21.46
IDEA StatiCa	16.08	16.24	18.46	19.64	21.60	21.60
Comparison	1.00	1.00	1.01	1.01	1.01	1.01

Table 9: Corresponding GMNIA calculation – SHS200×200×1, N

GMNIA – N	
Abaqus	67.73 kN
IDEA StatiCa	66.90 kN
Comparison	0.99

Table 10: LBA comparison – RHS300x150x1, M

LBA – M						
	EV1 in [kN]	EV2 in [kN]	EV3 in [kN]	EV4 in [kN]	EV5 in [kN]	EV6 in [kN]
Abaqus	3.19	3.19	3.41	3.43	3.80	3.85
IDEA StatiCa	3.24	3.24	3.48	3.50	3.90	3.96
Comparison	1.02	1.02	1.02	1.02	1.03	1.03

Table 11: Corresponding GMNIA calculation – RHS300x150x1, M

GMNIA – *M*	
Abaqus	10.01 kN
IDEA StatiCa	9.52 kN
Comparison	0.95

For the determination of the maximum resistance, the workflow MNA => LBA => GMNIA must be followed. Changes of the settings (e.g. loads, imperfection amplitude), even without a further calculation, will lead to a deletion of the results, either completely or partially, depending on the logical program level where the changes were carried out.
An LBA calculation typically leads to two central statements that are to be used for further calculations. First, the resulting eigenmodes are used as imperfection shapes for further GMNIA calculations in order to determine the maximum load bearing capacity. Comparisons with calculations from Abaqus showed a good agreement with calculations from IDEA StatiCa Member (see Tab. 9 and Tab. 11). The second statement of the LBA calculation is an amplification factor used to determine the critical buckling load. It is important to make sure that the selected load combination is not many times higher than the expected GMNIA load, otherwise the factor becomes inaccurate due to rounding and representation problems. However, this effect within the LBA analysis nor the high *c/t* values of the cross-sections had a noticeable influence on further GMNIA calculation.

6. Conclusions

The comparison between the calculations in the IDEA StatiCa Member software and the FEM program Abaqus showed generally small deviations in the LBA as well as GMNIA results with a maximum difference of 5% in individual cases. This level of deviation is common and well between the range of acceptability. Additional investigations regarding possible software limits were conducted by using considerably higher *c/t* values for the modeled member cross-sections. These showed only small differences with a maximum deviation of 5% in comparison with equivalent simulations in Abaqus.
Investigations on the choice of local and global imperfection amplitudes – according to code provision of EN 1993-1-1 [9], prEN 1993-1-1 [10] and EN 1993-1-5 [11] – leads to the following conclusions.

- In terms of local buckling the imperfection amplitude of *B*/400 showed a good agreement with the EN 1993-1-5 [11] "Winter curve" for plate buckling (case of constant compression in a plate supported on all four sides and in constant compression).
- Based on the calculations in section 4.2 a length proportional approach according to EN 1993-1-1 [9] is sufficient and safe sided when using the elastic design approach for

the evaluation of imperfection amplitudes. The same can be stated for the new formulation of the imperfection amplitude (see Eq. 1) regarding prEN 1993-1-1 [10]. It should be noted that β, the new reference bow imperfection (see Tab. 2), is not only dependent on the design approach but also the buckling axis "*y-y*" or "*z-z*". Within the scope of SHS and RHS profiles the values for amplitudes around *y-y* axis should be used regardless the buckling direction, since these are most consistent to the tabulated values of EN 1993-1-1, Tab 5.1 [9].

- When using the slenderness affine imperfection amplitudes according to EN 1993-1-1 [9] and prEN 1993-1-1 [10], it is recommended to use the plastic resistance. This approach requires that the magnitude of the relative slenderness is determined beforehand.

Additional investigations were carried out to provide a decision support, whether an interaction of local and global imperfections is required or not. Therefore, a safe-sided recommendation was formulated, introducing limit values (f_{lim}), which are derived from the relative distance of the analytical buckling curves of EN 1993-1-1 [9] and EN 1993-1-5 [11]. Whenever these limits are exceeded by the calculated factors *f* (see Eq. 3), global imperfections may be neglected in cases with $\alpha_{cr,loc} < \alpha_{lim,loc}$ for the consideration of square and rectangular hollow sections. It shall be noted that Annex C of EN 1993-1-5 [9], as well as prEN 1993-1-14 [14] (Design by FEM) make use of the "70%-rule" for the combination of imperfection modes and amplitudes. This rule postulates that *two* GMNIA calculations should be carried out when local + global interactive buckling may be dominant: one with 100% + 70% of the maximum specified amplitude in either case. In this report, however, we recommend avoiding this double calculation by using the amplitudes given in section 4.2 for global buckling and the reduced amplitude of *B*/400 (see section 4.1) for local buckling. This is sufficiently accurate and safe-sided for all cases that require a combined consideration of imperfections according to the presented flowchart in section 5.3.1, Fig. 11.

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