Comparative analysis of calculations in thin-walled structure design

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Abstract. This article focuses on reproducing normative calculation conditions through numerical methods and comparing these with outcomes obtained using specialized software for structural engineers. We analyse the basis of normative critical forces and stress values, including conditions of fixity, types of structures, and materials, and how these are represented in practical calculations and numerical modelling. The investigation is intended to enhance understanding between normative assumptions and their practical application in design, offering valuable guidelines for refining calculation methods.

1 Introduction

The issues in standards such as those in Eurocode 3 can be diverse and depend on specific aspects of structural design. We can identify several key areas where standards may provide either higher or lower values, or where potential deficiencies or ambiguities may be identified. Insightful analysis of studies that considered the dynamics of residual stresses, geometric imperfections, load eccentricity, and the specifics of support conditions in the context of cold-formed steel structures, opens new perspectives for reforming the regulatory framework, in particular the Eurocode. A thorough scientific approach to modeling the influence of these parameters proved their critical role in determining the limits of strength and stability of steel elements, which is not fully taken into account in modern design codes.

It was found that the residual stresses induced by the production process can lead to a significant decrease in the predicted bearing capacity, as a result of which the real strength of the structures can be underestimated by up to 20%. This indicates an urgent need to integrate more advanced residual stress assessment methodologies into standard design practices [1-3].

Further, the analysis of geometric imperfections and their influence on critical modes of bending and local buckling indicates significant variability in the response of structures to such imperfections. This demonstrates the need for a deeper understanding of the distribution and scale of these imperfections for the adaptation of regulatory strength criteria [4-5].

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Also, highlighting the problem of load eccentricity and its indirect effect on the effectiveness of the reference conditions will challenge the existing approaches in the Eurocode, which leads to a potential deterioration of the accuracy of calculations at the level of up to 15-25%. This is especially true for structures subject to complex loading scenarios, where traditional methods may not take into account the interaction between local and global buckling modes [6].

The need to improve the regulatory framework not only reflects the development of materials science and construction technologies, but also opens the way for more flexible and innovative approaches to design, which can significantly increase the efficiency of the use of materials and the energy efficiency of buildings.

2 Theoretical bases of calculations of critical forces and stresses

Detailed procedures are used to assess the stability of thin-walled closed section columns cold-bent in compression according to the theory of Eurocode 3, which take into account the flexibility of the walls and the possibility of local and general bending. Here are the basic steps used to calculate the stability of such columns:

- Determination of cross-section characteristics

Calculation of geometric characteristics of the section, including area, moments of inertia, radii of inertia, etc.

- Determination of thinness of elements

Calculation of thinness (λ) for various parts of the section (walls, shelves, etc.), which determines the ratio of length to thickness of these elements.

- Cross-section classification

Based on the thinness of the elements, a section class from 1 to 4 is determined, where 1 and 2 are completely resistant to local loss of stability, 3 is partially resistant, and 4 is slender, prone to local loss of stability.

- Calculation of critical normal stresses

For the overall stability of the column, critical stresses are determined using Eurocode formulas, which may include Euler's flexible formula for long bars, formulas for intermediate bars, etc.

- Calculation of coefficients

Use of coefficients to account for different types of stability losses, including local buckling, torsional buckling, etc.

- Determination of permissible load

Based on the estimated critical stresses and coefficients, the permissible load on the column is determined.

- This process requires accurate input data on the material, profile geometry and boundary conditions.

Also, important aspects for understanding metal structures are two quantities - critical and ultimate force. The critical force (P_{cr}) is defined as the maximum force a column can withstand without losing stability, i.e., before it buckles or bends laterally. The calculation of the critical force is based on ideal conditions, assuming the material's homogeneity and the absence of imperfections. The ultimate force (P_y), on the other hand, determines the maximum force before the column's failure, taking into account both elastic and plastic deformations, and depends on the real properties of the material. Calculating the ultimate force requires a more complex analysis, including the use of the finite element method to simulate the behaviour of the structure under load.

3 Tolerance in structures and its impact on calculations

For steel products, including cold-formed profiles, the tolerance norms are regulated by a series of European Union standards, in particular Eurocodes and EN standards. For cold-bent sections, standards such as EN 10219 [7] for cold-formed welded structural square and rectangular sections in non-alloy and fine-grained steel are commonly used.

Tolerances for the thickness of steel profiles (according to EN 10219):

- for a nominal thickness of less than 5 mm, the tolerance is usually ±10%,
- for a nominal thickness of 5 mm and more, the tolerance can be ±0.5 mm.

A tolerance for length - typically, the tolerance for the length of structural elements is ±50 mm for elements up to 6000 mm. For items over this length, tolerances may vary.

Geometric properties - tolerances for bending and torsion are also regulated by EN 10219 and depend on the dimensions of the profiles and the specific production conditions.

4 Modelling of thin-walled structures and analysis of results

For the purposes of this study, a cold-formed hollow section with nominal dimensions of 200 mm by 100 mm and a wall thickness of 3 mm, designated as RHS 200x100x3, fabricated from structural steel grade S235, was examined. Upon post-fabrication inspection and material testing, the section was found to have actual dimensions of 200.17 mm by 99.17 mm by 2.74 mm. The material testing revealed enhanced mechanical properties with a yield strength of 314 MPa and a tensile strength of 460 MPa, surpassing the standard requirements for grade S235. Compressive performance tests were conducted under centric loading conditions. The column was positioned on a simply support without any rigid end-connections. At the upper boundary, a hinge mechanism was implemented using a spherical bearing that facilitated the distribution of applied loads [8].

4.1 Modelling in SCIA Engineer

During the computational analysis performed with SCIA Engineer, a number of evaluations were performed: an ultimate limit state evaluation was performed, which included compression tests (according to EN 1993-1-1 [9] article 6.2.4), classification of the section design (according to EN 1993-1-1 article 5.2), the effective cross-section (according to EN 1993-1-5 [10] article 4.4) and compression tests were considered, followed by a stability test which included the classification of the structure for deflection (according to EN 1993 -1-1 article 6.3.1.1) and assessment of resistance to flat deflection in both directions.

Table 1. Resistance values of columns with different thickness and material properties.

	Geometrical characteristics				Material characteristics		$N_{c,rd}$
	t [mm]	A_{eff} [m^2]	$I_{y,eff}$ [m^4]	$I_{z,eff}$ [m^4]	f_y [MPa]	f_u [MPa]	[kN]
1	2.7	$1.123.10^{-3}$	$8.226.10^{-6}$	$2.234.10^{-6}$	314	410	352.66
2	3	$1.314.10^{-3}$	$9.109.10^{-6}$	$2.558.10^{-6}$	314	410	412.54
3	2.74	$1.151.10^{-3}$	$8.361.10^{-6}$	$2.277.10^{-6}$	314	410	361.55
4	2.7	$1.123.10^{-3}$	$8.226.10^{-6}$	$2.234.10^{-6}$	235	360	263.91
5	3	$1.314.10^{-3}$	$9.109.10^{-6}$	$2.558.10^{-6}$	235	360	308.79

The observed variation in slice thickness, although significant, remains within the specified tolerance limit of 10%, thus meeting the specified tolerance limits. The effect of this mismatch on the structural integrity and intermediate characteristics of the column was further analyzed. Table 1 shows the geometric and material characteristics and the obtained resistance values. If we look at how stability can loosen within the limits of geometric tolerances, we can also see the effect it has on thin-walled elements. Conducting a comparative analysis using the ultimate resistance values provided, we contrast them against the fifth scenario as the reference case ($N_{cr,rd}$ = 308.79 kN).

The first scenario ($N_{cr,rd}$ = 352.66 kN), with a 2,7 mm thickness within the 10% tolerance range, shows a 14% increase in ultimate resistance capacity compared to the baseline S235 with 3 mm thickness.

The second scenario ($N_{cr,rd}$ = 412.54 kN), with the exact ordered thickness of 3 mm, exhibits a 33.6% increase over the baseline, suggesting a potential for over-design and increased costs. The third scenario ($N_{cr,rd}$ = 361.55 kN), wit;h a slightly lesser thickness of 2.74 mm, demonstrates a 17.1% increase in resistance, indicating minor sensitivity to the decrease in thickness when material strength is higher. The fourth scenario ($N_{cr,rd}$ = 263.91 kN), near the tolerance limit for thickness, reflects a 14.5% reduction in resistance, raising concerns about potential underestimation of load-bearing capacity in design.

The fifth case represents the expected outcome for a profile with 3 mm thickness made from S235 steel, serving as the reference point for this analysis.

This assessment highlights that even minor deviations in thickness and material properties can notably affect the stability of structural components. Accurate specification adherence is paramount for ensuring structural integrity and cost-efficiency.

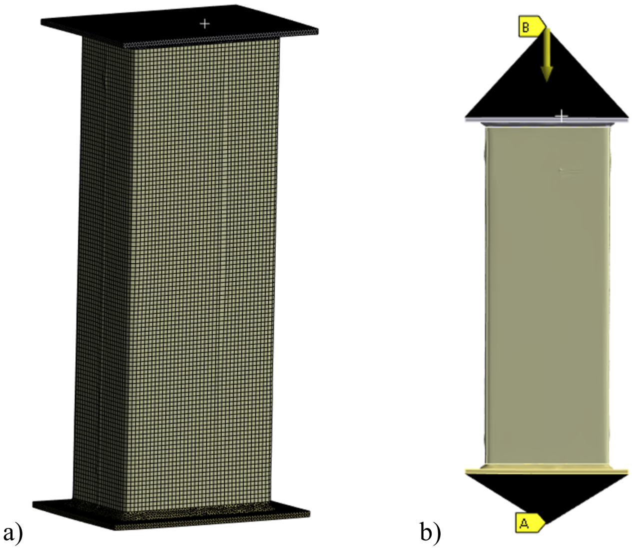
4.2 Modelling in Ansys

The normative validation of models calculated using the finite element method according to prBDS EN 1993-1-14 requires adherence to specific rules and procedures to ensure their adequacy and reliability for engineering applications. Models used for the design of metal structures must be validated by comparison with experimental results or verified numerical simulations. It is essential to ensure accurate modeling of geometry, material properties, and loading conditions. When modeling thin-walled elements shaped by cold forming and subjected to compression, it is necessary to include the effects of local deformations and surface irregularities, which affect the strength and stability of structures. Welded joints, which introduce additional stresses into the system, should also be considered.

In ANSYS, we created the precise geometry of the RHS column using 3D scanning. We divided the column into the top and bottom plates and the column itself. The bottom plate was modeled using the Auto Skin tool, which converts 3D scanned data into a solid body while preserving the weld geometry. To create the column, we used the Skin Surface tool, which generates surface geometry with high accuracy. To maintain the weld geometry, we removed the inner part of the material from the bottom plate in the joint area with the column and set the deviation tolerance to 0.05 mm. The results showed that the model's geometry is very precise.

In finite element simulations, we evaluated the element size to balance accuracy and computational efficiency. Smaller elements provide higher accuracy but increase computation time and memory requirements. We defined element sizes from 2 mm to 10 mm, with 2 mm elements providing the most accurate results but having the highest computational demands (Fig. 1 a)). The SHELL181 element was used for modeling the thin-walled structure, while the SOLID187 element was used for modeling the plates, allowing us to achieve a realistic representation of deformations and stresses.

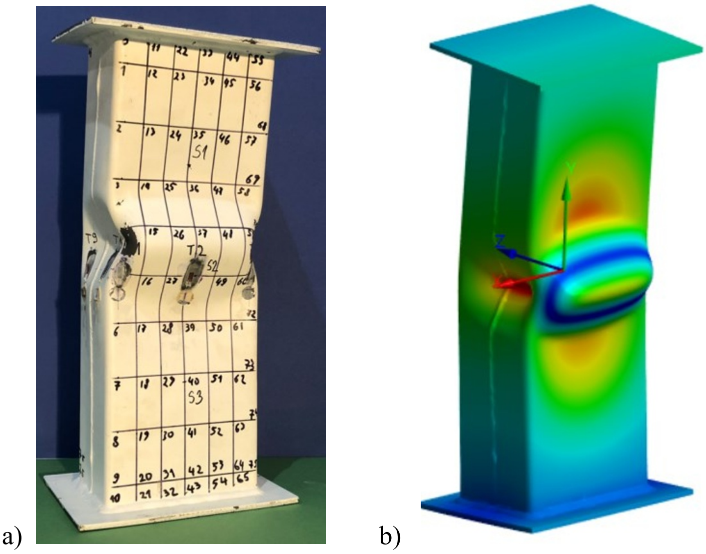
For defining boundary conditions, we used the Remote Displacement tool, which allows the application of displacements and rotations at a remote location in space, leading to more realistic modeling of loads and reactions. This approach improves the convergence and stability of the numerical solution (Fig. 1 b)).



a) b)

Fig. 1. Numerical Modeling: a) Finite Element Mesh, b) Boundary Conditions.

From the experiment, we also calculated the eccentricity and added it to the model, allowing us to obtain very accurate results that closely match the real behavior of the column. On Fig. 2, the comparison of deformations is shown.



a) b)

Fig. 2. Comparison of final deformation: a) Experiment, b) Ansys.

5 Conclusion

This article discussed various factors affecting the behavior of thin-walled columns under compression, including residual stresses, geometric imperfections, load eccentricity, and specific support conditions. Analyses showed that residual stresses could lead to up to a 20% underestimation of actual load capacity, geometric imperfections significantly impact critical modes of bending and local buckling, and load eccentricity can reduce calculation accuracy by up to 25%. Theoretical solutions indicate that manufacturing tolerances for thin-walled columns are not sufficiently precise, leading to significant deviations in structural stability and load capacity.

Engineering programs like SCIA Engineer calculate according to standards but do not account for manufacturing tolerances. For more accurate results, we used modeling in ANSYS, where more factors can be inputted to obtain precise solutions. This approach is, however, much more complex, demanding, and time-consuming, requiring accurate data on material properties, thicknesses, and dimensions. This way, we can more accurately simulate the behavior of structural elements and identify critical factors affecting their stability.

Theoretical solutions are not sufficiently precise, indicating the need for their improvement and updating to better account for real conditions and manufacturing tolerances. On the other hand, numerical solutions are very complex and demanding in terms of time and resources. Therefore, it is necessary to find a balance between theoretical and numerical approaches, which will enable more accurate and efficient structural designs.

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References

1. J.-L. Ma, T.-M. Chan, B. Young, J. Constr. Steel Res. 109, 152-165 (2015)
2. M. Jandera, J. Machacek, Thin-Walled Struct. 83, 12-18 (2014)
3. L. Jaamala, K. Mela, J. Laurila, M. Rinne, P. Peura, J. Constr. Steel Res. 189, 107108 (2022)
4. R. Aktepe, B. Guldur Erkal, J. Constr. Steel Res. 207, 107942 (2023)
5. L. Jaamala, K. Mela, J. Tulonen, A. Hyvärinen, J. Constr. Steel Res. 198, 107569 (2022)
6. Z. Sadowský, J. Križan, Thin-Walled Struct. 131, 12-18 (2018)
7. EN 10219-1:2006 Cold formed welded structural hollow sections of non-alloy and fine grain steels - Part 1: Technical delivery conditions
8. E. Hodovaneţs, M. Al Ali, V. Kvočak, AIP Conf. Proc. 2887, 020065 (2023)
9. EN 1993-1-1 Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings (2006)
10. EN 1993-1-5 Eurocode 3: Design of steel structures - Part 1-5: General rules - Plated structural elements (2006)