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Effect of Intermediate Stiffeners in an Optimization of Axially Compressed Built-up Thin-Walled Column Cross-Sections According to the Eurocode 3

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Abstract

This paper aims to propose an optimized thin-walled built-up cross-section for axially compressed columns, which can be feasibly produced and utilized in building assemblies. The European standard Eurocode 3 [1] was employed, along with an optimization solving algorithm, to calculate the performance of axially compressed thin-walled columns. The analysis considered the buckling capacity of the column, encompassing local, distortional, and global buckling modes. 3 types of box cross-sections were examined: without web stiffeners, with web stiffeners bent inwards, and with web stiffeners bent outwards. The cross-sections were constructed by connecting 2 "C" type or "Sigma" type profiles through their flanges. In the calculations, the thickness of the overlapping parts of the flanges was assumed to be equal to the thickness of the profiles. Experimental investigations have shown that this assumption, where the overlapping parts of the flanges are considered equal to the profile thickness, is conservative and reliable [2]. Consequently, the built-up cross-section can be treated as one rigidly connected entity [3]. The results of the calculations reveal that the optimized built-up axially compressed column cross-section with web stiffeners exhibits a higher level of effectiveness, with a cross-sectional area up to 23% smaller compared to the optimized cross-sectional area of columns without web stiffeners.

Keywords

Cold-Formed Structures, Eurocode, Stability of Cross-Sections, Members and Frames, Slender Members, Local Buckling, Distortional Buckling

1 Introduction

The objective of this paper is to optimize the cross-section of built-up thin-walled columns suitable for civil engineering applications. Thin-walled cross-sections represent a specialized structure that poses challenges in analysis due to their high slenderness. In steel columns, the buckling strength of the member or its cross-section parts typically determines their performance. However, thin-walled structures introduce an additional buckling mode known as distortional buckling. The primary buckling types observed in steel structures include global buckling of an element and local buckling of a cross-section. Analytical and numerical methods have been developed to calculate the behavior of compressed thin-walled cross-sections, taking into account the instabilities inherent in such configurations. Commonly used Direct Strength Method (DSM) is developed to calculate thin-walled columns and beams under compression and bending considering local and distortional buckling modes [4], [5]. The method is given in the American design code AISI [6] and the Australian design code [7]. Another calculation method is given in the Eurocode 3 [1] which provides analytical methods to calculate thin-walled cross-sections including the resistance to buckling evaluating effective cross-section areas and stiffener impacts [8]. Other methods calculating thin-walled structures include Finite Element Method [9] and modified finite element methods: Generalised Beam Theory [10, 11], Finite Strip Method [12].

Numerous investigations have been conducted in search of an optimal thin-walled cross-section [13-15]. However, a significant challenge lies in the limited practical feasibility and utilization of such cross-sections in civil engineering applications. Other optimizations have focused on single profiles, following the guidelines of Eurocode 3 [16] or employing the Direct Strength Method [17]. Experimental studies have also been conducted on thin-walled built-up columns. Kherbouche and Megnounif [3] analyzed columns featuring a cross-section composed of "C" profiles connected by thin-walled plates, while Zhang and Young [18]

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and Deepak et al. [19] investigated columns with a cross-section formed by two "C" or "sigma" profiles, resulting in an I-shaped configuration. In another study, Liu and Zhou [20] added an additional "C" profile to the I-shaped cross-section. Meza et al. [21, 22] examined columns comprising "C" and plate profiles, leading to closed or hybrid cross-sections. Liao et al. [23] conducted experiments by connecting two, three, or four "C" profiles within a single cross-section. Zhang and Young [2, 24] analyzed built-up cross-sections made of "C" or "Sigma" profiles, forming closed configurations with intermediate web stiffeners bent inwards or outwards. Despite these contributions, a notable research gap exists regarding the optimization of thin-walled built-up cross-sections within the framework of Eurocode 3. Furthermore, the effect of stiffeners on axially loaded thin-walled built-up columns when the cross-section is optimally designed remains insufficiently analyzed.

2 Calculation procedure of a compressed thin-walled column according to the Eurocode 3

Eurocode 3 part 1-3 [1] gives the method for the calculation procedures of the cold-formed steel structures. The methodology provides geometrical limits of the structure for which the calculation methods are viable. It provides the cross-sectional strength as well as the buckling strength calculation of the compressed thin-walled members. The buckling strength is the main limitation in this article because columns with high slenderness are analyzed. Eurocode 3 includes the calculation of the local and distortional buckling of a thin-walled cross-section and the global buckling of a member when considering the effective area of the cross-section.

The local buckling is a buckling mode where individual plate parts of the cross-section deform. The calculation procedure for local buckling is implemented using the effective width concept. The stresses in the compressed plates are considered to accumulate at the corners of the cross-section. Idealized effective cross-section parts at the edges with maximum stresses and ineffective parts at the middle of the plate parts of the cross-section with no stresses are calculated. Eurocode 3 part 1-5 [25] gives an additional procedure for determining the effective width of the compressed plate parts of the cross-section.

The distortional buckling is a buckling mode where cross-section parts rotate with respect to each other at the junction of the parts. The calculation procedure for distortional buckling is implemented by calculating the stiffness of the longitudinal stiffeners. The stiffener is considered to be supported on a linear spring support. The procedure to define the stiffness of the stiffener is given to calculate the critical stress of the stiffener. Therefore, the thickness of the stiffener is reduced to take the distortional buckling into consideration of the buckling calculation.

The global buckling mode is a common buckling mode for columns with a high slenderness. This mode appears with a shift or a rotation of whole cross-section without any larger cross-section deformations. The Eurocode 3 provides the general calculation of an axially compressed column considering the buckling mode reduction factor:

$$N_{b,Rd} = \frac{\chi A_{eff} f_y}{\gamma_{M1}} \qquad (1)$$

where χ is the reduction factor for buckling mode, A_{eff} is the effective area of the cross-section, f_y is the yield strength of the material, γ_{M1} is the partial factor for resistance of members to instability.

The reduction factor for buckling mode is calculated considering the slenderness and the imperfection factor for the buckling curves. The calculations for the local, distortional, and global buckling of the axially compressed thin-walled column written above are included in the optimization of the cross-section in this article.

3 Optimization of a built-up thin-walled column

It is challenging to find the optimal thin-walled cross-section column, because its strength is always limited by the buckling strength of the column. Different optimization procedures exist, which are grouped to sizing, shape and topology optimizations [26]. This paper employs the sizing optimization of a thin-walled built-up closed cross-section. The moment of inertia of the cross-section increases as the width and the height of the cross-section increases, and so does increase the ineffective area of the cross-section web and flange. The ineffective area of the cross-section is decreased when the thickness-to-width ratio of the cross-section is increased. The geometry of the cross-section and the thickness of the cross-section are dependent on each other and must be considered in combination to achieve the maximum moment of inertia of the cross-section to the main cross-sectional axes and minimum ineffective area of the cross-section. This way the gross cross-sectional area should be minimized while sustaining the required strength of the column which is highly dependent on the moment of inertia of the cross-section.

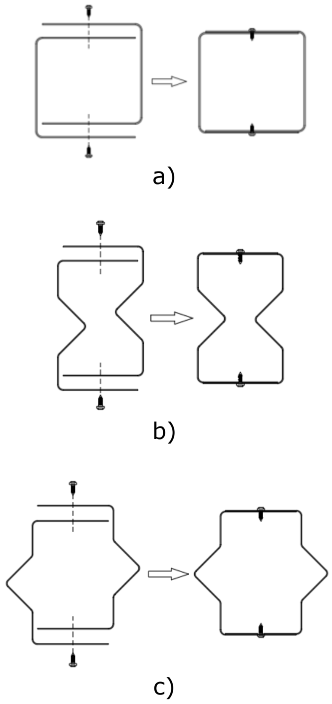

Figure 1 Thin-walled built-up cross-section column assembly: a) – square cross-section, Type A; b) – closed cross-section with web stiffeners pointing inwards, Type B; c) – closed cross-section with web stiffeners pointing outwards, Type C

A square cross-section without stiffeners and square cross-section with web stiffeners pointing inwards or outwards are optimized. Such cross-sections can be produced by connecting two "U" or "Sigma" profiles with self-drilling screws. Cross-section assembly is given in the Figure 1. The effective thickness of the overlapping parts of the cross-section is complicated to determine, because it is dependent on different factors – overlapping length, number of the connector rows and spacing of the connectors. Zhang & Young [2, 18] analyze a similar case, where two profiles overlap each other at the flanges and are connected with a single row of self-drilling screws. They claim that the effective thickness of the overlapping part of the cross-section taken equal to the thickness of the profile is conservative and reliable. Moreover, Kherbouche & Megnounif [3] made a conclusion, that when cross-section is analyzed with the contact area cross-section thickness equal to the profile thickness, the built-up cross-section can be considered as one rigidly connected section.

4 Formulation of the optimization problem

The optimization problem of this paper is the minimum of the cross-sectional area of the axially compressed built-up thin-walled column. The axial load and the length of the column are picked by the authors for the task. The column is considered simply supported; the effective length of the column is equal to the length of the column according to both axes of the cross-section. The variables of the problem are the geometry and the thickness of the cross-section. Three types of the closed cross-sections are optimized, showed in the Figure 1. The Type A is a rectangular cross-section without stiffeners, the Type B is a rectangular cross-section with a web stiffener curved inside of the cross-section and the Type C is a rectangular cross-section with a web stiffener curved outside of the cross-section. It is logical, that optimal cross-section will always be symmetrical according to the y-y and z-z cross-sectional axes, because the load is axial.

The buckling strength which includes calculations for local, distortional, and global buckling modes for the axial compression is the optimization constraint for each type of the columns. Additional constraints for the Type B and the Type C cross-sections include constraint for the geometry of the stiffener to ensure the plate elements of the stiffener would not be affected by the local buckling.

The built-up cross-section of the column is formed by overlapping the entire flanges of the cross-section, resulting in a gross flange thickness that is twice as thick as that of a single profile. For the reasons, given in the section 3 of this paper, the cross-section properties and strength are calculated as if it were a single rigid cross-section with a thickness equal to that of the individual profiles. To validate the accuracy of the calculation algorithm employed in this study, a comparison was made with experimental results conducted by Zhang & Young [2], involving a similar cross-section type to the Type B cross-section examined in this research. The experimental test results of these authors that were used for the comparison involved columns of various heights (300 mm, 2000 mm, and 3200 mm) with a nominal thickness of 1 mm. The calculated buckling strength of the columns using the algorithm in this study was found to be 5.8% to 20.6% more conservative compared to the experimental test results. This indicates that the assumption of evaluation of the flange thickness is appropriate and that it ensures a conservative approach in structural analysis.

The minimization function is the gross cross-section area. Optimization problem is solved using a nonlinear programming solver. Function fmincon in the MATLAB R2022b [27] software is used to find the minimum of constrained nonlinear multivariable function:

$$\min_{x} f(x) \; subject\ to\ constraints \begin{cases} c(x) \le 0 \\ ceq(x) = 0 \\ A \cdot x \le b \\ Aeq \cdot x = beq \\ lb \le x \le ub, \end{cases} \qquad (2)$$

where x, b, beq, lb and ub are vectors, A and Aeq are matrices and $c(x)$, $ceq(x)$ and $f(x)$ are functions that return vectors. Vector x is the solution of the optimization, which is the cross-section geometry coordinates and thickness of the cross-section for this optimization problem. Functions $c(x)$ and $ceq(x)$ are constraint functions, which are the strength and geometry constraints for this optimization problem. Matrices A, Aeq and vectors b, beq are linear constraints, which are unused in this optimization problem. Vectors lb and ub are the lower and upper bounds of the solution x of the function.

5 Optimized examples

Axially compressed thin-walled built-up columns have been optimized. The length of the columns was accepted 3 meters. The properties of an S355 grade steel have been used for the calculations. Loads of 50 kN, 100 kN and 200 kN have been added for each type of the cross-section. The starting geometry for the optimization calculations is given in the Figure 2.

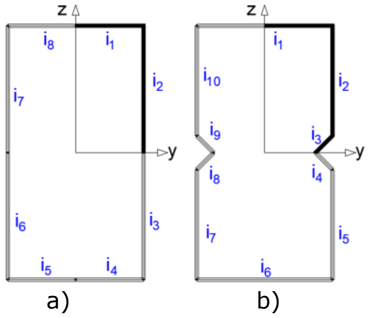

Figure 2 Starting cross-section geometry of the optimized columns: a) – rectangular cross-section without stiffeners; b) rectangular cross-section with a web stiffener curved inside of the cross-section

The cross-section area according to the optimization results (Table 1) was compared between different cross-section types of the column. Optimized Type B cross-section areas were 16%, 13% and 8% smaller for respectively 50 kN, 100 kN and 200 kN, when compared to the Type A cross-section areas. The optimized Type A, B and C column cross-sections are given respectively in Figures 3, 4 and 5. Optimized type C column cross-section showed the best effectiveness of the analyzed types. The optimized cross-section area of the Type C columns were respectively 23%, 24% and 22% smaller than the Type A cross-sections.

The reason for the higher effectiveness of the Type C cross-section can be attributed to its similar cross-sectional area compared to the Type B, but with stiffeners positioned further from the center of gravity. This configuration results in a higher moment of inertia, enhancing the overall structural performance. Furthermore, the Type C cross-section was reinforced with web stiffeners, distinguishing it from the Type A cross-section. Figure 6 provides a comparison of the optimized cross-section areas for different column types under 50 kN, 100 kN, and 200 kN loads.

For the Type A cross-sections, the width and height of the cross-sections remained consistent across different load sizes. This was because the buckling strength of the cross-section was the same along both axes, and the overlapping part of the cross-section was calculated with a thickness equal to that of a single profile.

Both the A and C types of optimized cross-sections exhibited a greater width than height. The buckling strength of the columns was equivalent to the optimization objective load along both axes of the cross-section. The optimization algorithm developed in this study not only enables the selection of an appropriate web stiffener with an optimal cross-section thickness to withstand local buckling but also facilitates the selection of cross-section geometry to ensure the moment of inertia is the same along both cross-section axes.

Table 1 Cross-section area of the optimized cross-section types

Cross-section type	Cross-section area, mm²		
	under 50 kN axial load	under 100 kN axial load	under 200 kN axial load
Type A	561.7	908.1	1479.5
Type B	471.6	785.5	1354.3
Type C	432.7	692.0	1157.2

During the analysis of cross-section parts without stiffeners, it was consistently observed that they had an ineffective width in the middle. However, when cross-sections with web stiffeners were analyzed, the ineffective width in the webs was significantly minimized, almost approaching zero. Under 50 kN and 100 kN axial loads, the effective area of the stiffeners in the B and C types of cross-sections was reduced due to distortional buckling.

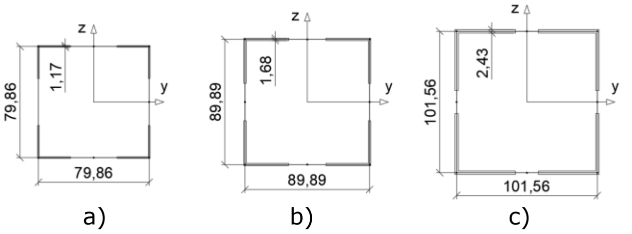

Figure 3 Cross-section geometry of optimized Type A column: a) – column under 50 kN axial load; b) – column under 100 kN axial load; c) – column under 200 kN axial load

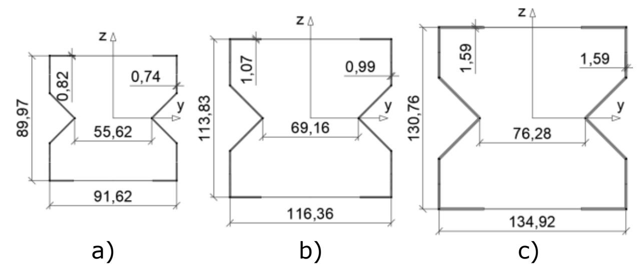

Figure 4 Cross-section geometry of optimized Type B column: a) – column under 50 kN axial load; b) – column under 100 kN axial load; c) – column under 200 kN axial load

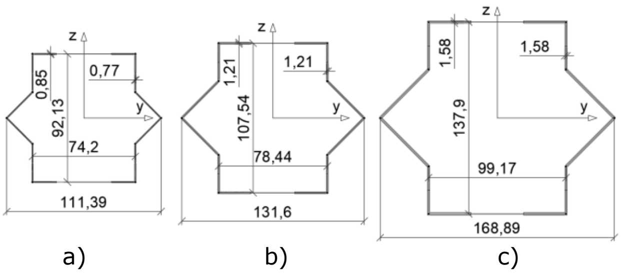

Figure 5 Cross-section geometry of optimized Type C column: a) – column under 50 kN axial load; b) – column under 100 kN axial load; c) – column under 200 kN axial load

The optimized Type A cross-section thickness was about 30% thicker when compared to the optimized Type B and Type C cross-section thickness. But the Optimized Type A cross-section had both width and height of the cross-section smaller than the optimized B and C Types of cross-section. These parameters can be determining when considering practical applications of the cross-sections.

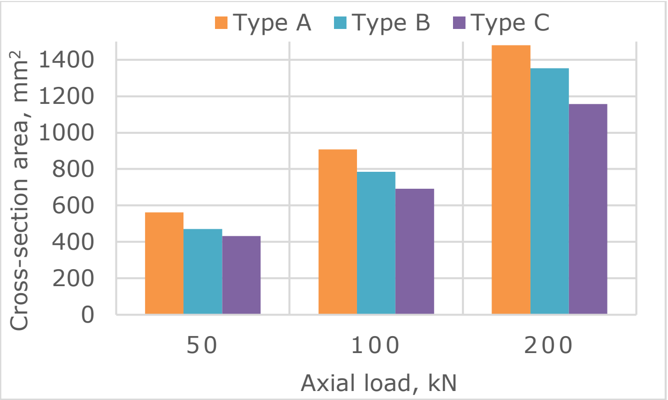

Figure 6 Comparison of the cross-section area of different types of columns under 50, 100 and 200 kN axial load. The length of the columns is 3 m

Conclusion

In this study, three different built-up thin-walled column cross-sections were optimized using the calculation procedure outlined in Eurocode 3 for axially compressed thin-walled columns. The incorporation of web stiffeners in the cross-section design proved to be highly effective, as it enabled achieving the same load-carrying capacity with a reduced cross-sectional area compared to the cross-section without stiffeners. The optimized cross-sectional area of the built-up thin-walled columns with stiffeners was found to be up to 23% smaller than that of the columns without web stiffeners.

Furthermore, cross-sections with web stiffeners bent outwards exhibited a reduction in cross-sectional area of up to 15% compared to the cross-sections with web stiffeners bent inwards. The effectiveness of cross-sections with stiffeners increased with higher axial compression loads applied to the columns. Additionally, a notable observation was the significantly thicker cross-section of the analyzed column without stiffeners when compared to the cross-sections with stiffeners. On the other hand, both types of cross-sections with stiffeners, whether the web stiffeners were bent inwards or outwards, exhibited similar cross-section thicknesses. These findings suggest that cross-sections with stiffeners are not only structurally advantageous but also more practical to produce and handle.

Overall, this study highlights the significant benefits of incorporating intermediate stiffeners in the optimization of axially compressed built-up thin-walled column cross-sections according to Eurocode 3 guidelines. The utilization of web stiffeners allows for achieving efficient load-carrying capacity while reducing the cross-sectional area, thus offering potential cost savings and material optimization in structural design. The obtained results contribute to the understanding of the behavior and performance of such optimized cross-sections, providing valuable insights for future applications in civil engineering and construction projects.

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