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Analysis of Load Eccentricity in Cold-Formed Steel RHS Columns under Compression Considering Geometric Imperfections

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Abstract

This research investigates the impact of hinged and fixed boundary conditions on the behavior of cold-formed steel rectangular hollow section (RHS) columns under eccentric compression. Theoretical analysis and numerical experiments were conducted to study the effects of geometric imperfections and eccentric loading on deformation and failure mechanisms. The findings highlight the significant influence of boundary conditions and geometric imperfections on the columns' stability and load-bearing capacity. These results emphasize the need for careful consideration of these factors in the design and analysis of cold-formed steel structures.

Keywords: eccentricity, cold-formed steel, geometric imperfections, boundary conditions, load-bearing capacity

1 Introduction

The way a column is supported at its ends—whether it is hinged, fixed, or a combination of both—significantly affects its stability, load-bearing capacity, and overall deformation behavior under applied loads.

Hinged boundary conditions allow for rotations at the column ends, which can result in greater deflections and reduced stability compared to fixed conditions, where the ends are restrained from rotating. In practical applications, hinged supports are often used where connections permit some degree of rotational freedom. This can be advantageous in certain designs, but it also introduces complexities in predicting the column's behavior under loads, especially when eccentric loading is involved.

Fixed boundary conditions, on the other hand, provide higher stability as they restrict rotations at the ends of the column. This increased rigidity helps in maintaining the structural integrity and enhancing the load-bearing capacity. Columns with fixed supports are generally more stable and less prone to buckling under axial loads. However, the trade-off is the potential for higher internal stresses, which must be carefully managed in design.

The significance of boundary conditions becomes even more pronounced when dealing with slender columns. Slender columns, characterized by a high length-to-cross-sectional dimension ratio, are more susceptible to buckling. The type of boundary condition can drastically influence the critical load at which buckling occurs. For slender columns, even small eccentricities in loading can lead to significant bending moments, increasing the risk of instability. Therefore, accurately modeling and understanding

the effects of boundary conditions is crucial for the safe and efficient design of slender structural elements.
Extensive research has been conducted to explore the impact of boundary conditions on column stability. Numerical methods, such as those implemented in finite element software like ANSYS, have been instrumental in predicting the complex interactions between boundary conditions, load eccentricities, and geometric imperfections.

2 Theory of hinged and fixed boundary conditions

Boundary conditions significantly influence the behavior and ultimate bending strength of thin-walled structures. Previous studies [1] subjected columns to various boundary conditions, demonstrating their impact on ultimate bending strength. For instance, columns with fixed boundary conditions exhibited higher bending loads due to increased axial stiffness. Conversely, boundary conditions allowing rotations at the loaded end result in decreased ultimate bending strength due to increased deformability.
In our study, two types of boundary conditions were examined: hinged and fixed supports. It was observed that the experimental results for columns with fixed supports exhibited a much closer agreement with theoretical predictions. Consequently, the primary focus of this paper is on columns with hinged boundary conditions. This choice was made because the hinged boundary conditions produced more complex and illustrative deformation patterns, which are essential for comprehensively understanding the effects of eccentric loading and geometric imperfections on local stability. This detailed focus on hinged conditions allows for a deeper investigation into the local buckling phenomena and their implications for structural design and analysis.
When a column is hinged at one end only, the boundary conditions at that end do not provide stiffness against bending moments. This causes greater deformations and bending due to the inability of the support to resist lateral forces from eccentric loading.
For columns two-side hinged, loading may cause buckling in the direction of the weaker axis, especially if there is an eccentricity of the load. In analyzing such columns, special attention should be given to longer, less rigid walls, which are more prone to local stability losses and offer less resistance to lateral bending.

3 Experimental studies

In our investigation, we selected short columns with dimensions of 160 mm by 100 mm and a length of 450 mm, constructed with a steel thickness of 2.74 mm, as the primary focus was to examine local resistance phenomena. The decision to utilize short columns was driven by the specific intent to isolate and analyze localized effects and behaviors under compressive loads, without the complexities introduced by global buckling that longer columns might exhibit.
The chosen cross-section dimensions were specifically selected to ensure the column could be classified as slender, falling into the Class 4 category according to Eurocode specifications.
It is recognized that for longer columns, the influence of eccentricity on global buckling would likely be more pronounced. Longer columns would introduce additional variables related to overall stability, making it challenging to isolate local effects [2].
The geometric accuracy of the column was verified using 3D scanning, and the results were integrated into numerical models for further analysis. Material testing revealed enhanced mechanical properties, including a yield strength of 314 MPa and a tensile strength of 460 MPa, exceeding the standard requirements for grade S235.
To test the column, two-sided hinged boundary conditions were employed (Figure 1), simulating realistic operational scenarios. Special attention was given to the influence of geometric imperfections,

such as small deviations from ideal shapes and sizes, which can affect the structure's strength and stability under load.

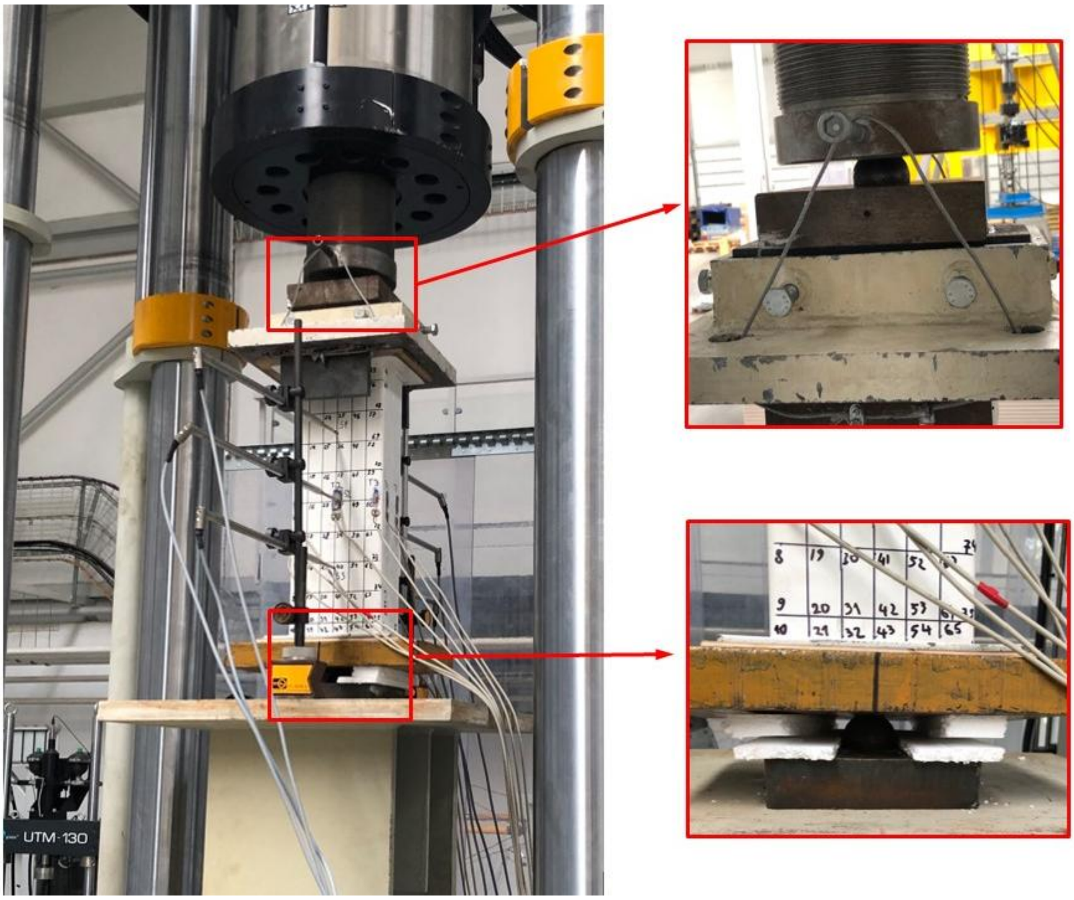


Figure 1: Two-sided hinged boundary conditions of research column

3.1 Measurement of Eccentricity

The measurement of eccentricity involved installing strain gauges around the column's circumference (Figure 2) to capture deformations during loading.
Strain gauges measured deformation at specific points, which was used to calculate stress. Using these stress values, the moments were determined, and from these, the eccentricity was calculated. This analysis helped understand the impact of eccentric loading on the column's behavior.
The strain gauge data revealed uneven stress distribution, indicating load eccentricity (Figure 3). This eccentricity can be attributed to factors such as material differences or varying thicknesses of the opposite wider walls of the column, as well as initial geometric imperfections.
Special attention was given to the top welded plate, which may have imperfections and may not be parallel to the column's base. When the load is applied, it initially transmits through these imperfections, causing the column to deviate towards the more protruding side, resulting in an uneven stress distribution around the perimeter. This can lead to local instability and a decrease in the column's overall load-bearing capacity.
Additionally, if the plates are not welded parallel, it can misalign the column under load. Consequently, the wall pressed by the plate may receive more stress, increasing eccentricity and complicating the calculation of the column's strength and stability [3-4].

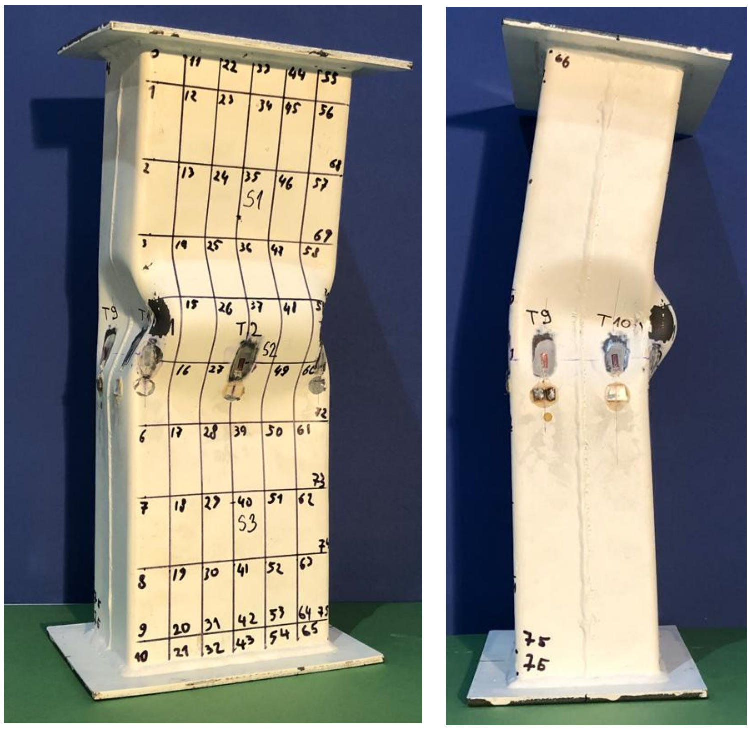


Figure 2: Deformation form from experiment

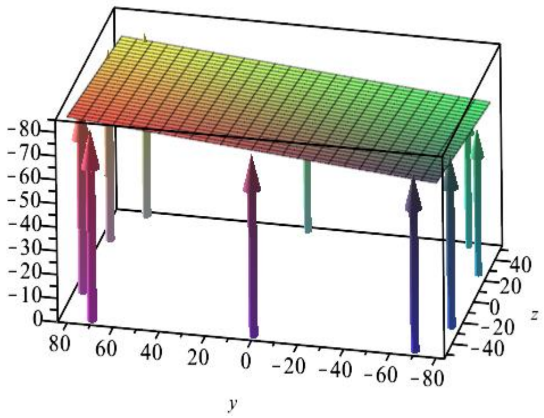


Figure 3: Stress distribution from experiment

4 Comparative analysis of numerical and experimental results

For a deeper analysis, we employed numerical modeling techniques, such as in ANSYS, to replicate the experimental conditions and test how accurately the numerical models predict the behavior of real structures. Our model included simulations incorporating geometric imperfections, boundary conditions, and nonlinear material properties to evaluate their effects on critical loads and deformation behavior.

The following tables present data on the influence of eccentricity on the critical force and total deformation of the RHS column, obtained through numerical simulation. Eccentricity values range from -30 mm to +30 mm, indicating the distance from the center of the column where the force was applied.

The tables highlight data for two different loading conditions: when the eccentricity is applied only from the top and when it is applied from both ends.

Table 1: Eccentricity applied only from the top.

Eccentricity [mm]	Force-numerical [kN]	Total Deformation [mm]	Type of Deformation	Force-numerical / Force-experiment
-30	251.59	13.45	4 (a)	0.859
-20	284.18	14.32	4 (a)	0.970
-10	324.49	15.22	4 (a)	1.108
-8	332.04	15.41	4 (a)	1.133
-6	342.92	15.41	4 (a)	1.170
-4	352.44	15.77	4 (a)	1.203
-2	360.83	15.96	4 (a)	1.232
-1	366.46	16.04	4 (a)	1.250
-0.75	367.40	12.84	4 (b)	1.254
-0.5	368.21	8.89	4 (c)	1.257
0	369.53	8.91	4 (c)	1.261
0.5	371.45	8.97	4 (d)	1.268
1	373.74	8.99	4 (d)	1.276
2	375.07	8.91	4 (e)	1.280
2.5	374.21	13.26	4 (f)	1.278
4	368.07	15.88	4 (g)	1.256
6	358.17	15.68	4 (g)	1.222
8	347.48	15.49	4 (g)	1.186
10	335.80	15.31	4 (g)	1.146
20	294.46	14.41	4 (g)	1.005
30	259.86	13.56	4 (g)	0.887

The following tables present data on the influence of eccentricity on the critical force and total deformation of the RHS column, obtained through numerical simulation. Eccentricity values range from -30 mm to +30 mm, indicating the distance from the center of the column where the force was applied. The tables highlight data for two different loading conditions: when the eccentricity is applied only from the top and when it is applied from both ends. This approach allows for a comparison of how unilateral and bilateral eccentricity affects the column's bearing capacity and deformation.

The experimental data showed an ultimate force of about 293 kN and a calculated eccentricity at the middle of the column of about 8 mm. When we compare these values with the numerical data in the tables, we observe that the force corresponding to an eccentricity of 10 mm matches closely with the experimental ultimate force. This suggests that using these calculations provides a reasonable approximation that can be compared with experimental results.

Table 2: Eccentricity applied from both top and bottom.

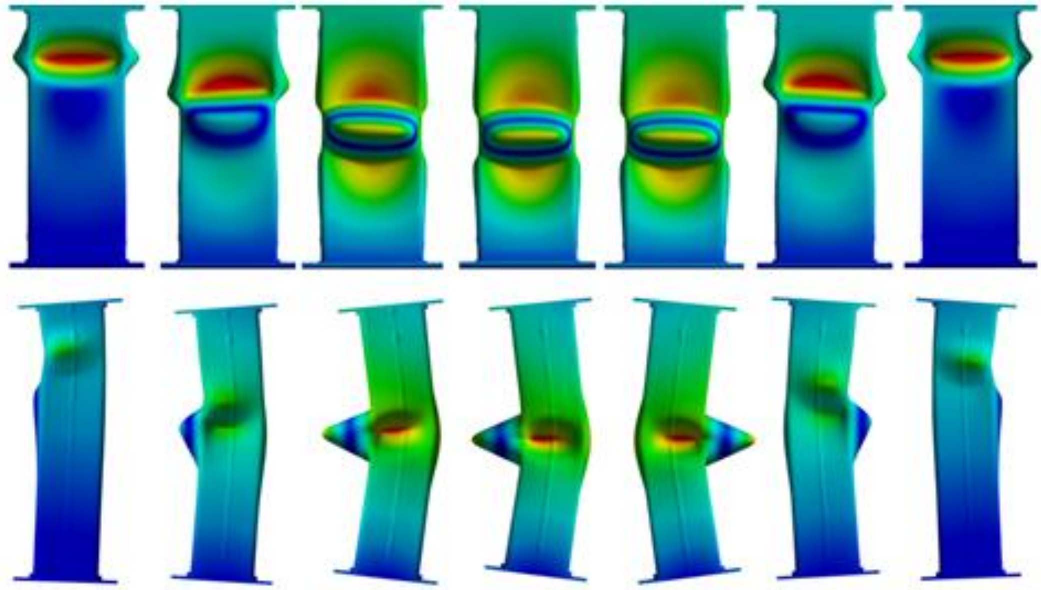
Eccentricity [mm]	Force-numerical [kN]	Total Deformation [mm]	Type of Deformation	Force-numerical / Force-experiment
-30	208.02	12.58	5 (a)	0.710
-20	244.17	13.61	5 (a)	0.833
-10	295.25	14.77	5 (a)	1.008
-8	308.41	15.02	5 (b)	1.053
-6	322.00	15.28	5 (b)	1.099
-4	337.56	15.43	5 (b)	1.153
-2	353.77	8.71	5 (c)	1.207
-1	361.81	8.81	5 (c)	1.235
-0.75	363.21	8.82	5 (c)	1.240
-0.5	366.40	8.86	5 (c)	1.250
0	369.53	8.91	5 (d)	1.261
0.5	374.01	8.97	5 (e)	1.276
1	374.70	8.83	5 (f)	1.279
2	367.58	8.71	5 (f)	1.255
2.5	368.36	12.81	5 (f)	1.258
4	350.87	14.48	5 (g)	1.198
6	335.13	14.57	5 (g)	1.144
8	320.58	14.33	5 (g)	1.094
10	306.27	14.09	5 (g)	1.045
20	252.25	13.02	5 (g)	0.861
30	214.30	12.07	5 (g)	0.731

Figures 4 and 5 depict the types of deformations occurring in a column under eccentric loading from the top only and from both top and bottom simultaneously.

Certain deformation characteristics correspond to each type of eccentricity. For example, Figures 4(a) and 5(a) show a column with an eccentricity of -30 mm, where the strain shape is symmetrical about the vertical axis but differs in stress form and distribution. In both cases, stress concentrations are noted in areas of greatest curvature.

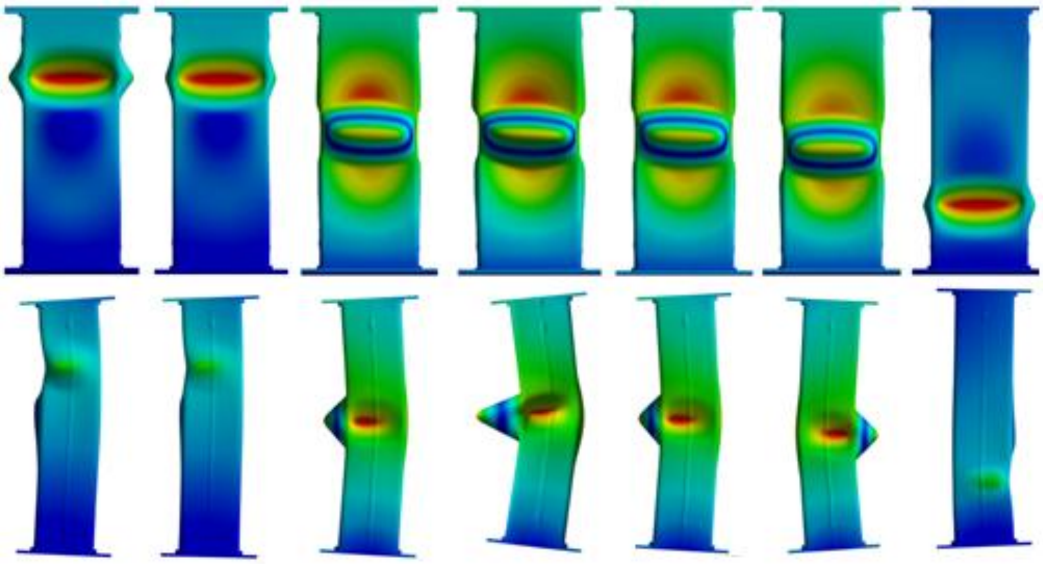
By changing the boundary conditions from one-sided to two-sided, the stress distribution and deformation shape of the column change. For instance, in Figure 5(b) with an eccentricity of -8 mm from the top and bottom, deformation is concentrated in the middle part of the column and is smaller at the ends, compared to Figure 4(a) where such eccentricity is applied only on one side.

Special attention should be paid to Figure 5(g), which illustrates a significant change in column behavior at high positive and negative values of eccentricity. The deformation indicates a significant asymmetry in the column's response, suggesting a critical effect of load eccentricity on structural stability. This may be due to increased lateral bending and additional moments introduced into the system, especially noticeable with eccentricity.



a) b) c) d) e) f) g)

Figure 4: Type of deformation with eccentricity at top



a) b) c) d) e) f) g)

Figure 5: Type of deformation with eccentricity at top and bottom

5 Conclusion

This study provides new insights into the behavior of cold-formed steel columns with a rectangular hollow section under eccentric compressive loading. The consideration of geometric imperfections and boundary conditions, as demonstrated by experimental and numerical models, significantly influences the magnitude of critical loads and the deformation character of the column. Analysis of the data revealed

that manufacturing and installation imperfections, such as wall thickness variations and non-parallelism of welded plates, lead to a reduction in load-bearing capacity and may cause unexpected forms of stability loss.
Moreover, it was found that geometric imperfections significantly change the internal stress distribution in the column, indicating the necessity to consider these parameters in design and analysis. The presented results of experiments and ANSYS modeling confirm that existing methods of calculating column strength may be insufficient if not all possible influences and imperfections are considered.
Additionally, the types of deformations identified at high eccentricity values indicate an asymmetric response of the column to loading, which may suggest a critical impact of load eccentricity on structural stability.

Acknowledgments

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