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Experimental investigation of the behavior of cold-formed steel omega-section columns under axial load

Soğukta şekil verilmiş çelik omega kesitli kolonların eksenel yük etkisi altındaki davranışlarının deneysel olarak incelenmesi

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Abstract
This study aims to experimentally investigate the buckling behavior and load-bearing capacities of cold-formed steel (CFS) omega-section columns under axial load. Within the scope of the research, 11 omega column specimens with thicknesses ranging from 1.75 mm to 3 mm were integrated with corrugated silo wall sheets of various thicknesses and subjected to axial compression tests. The experiments were designed to analyze the effects of lateral restraint conditions and column thickness on load-bearing capacity, post-elastic behavior, and failure modes. The findings fill a significant gap in literature by demonstrating the interactive performance of omega sections with secondary elements like silo walls. This study provides critical data for the design of these thin-walled members in modern construction applications.

Keywords: Cold-formed steel, Column, Experimental study, Omega section, Corrugated wall

Öz
Bu çalışma, soğukta şekil verilmiş çelik (CFS) omega kesitli kolonların eksenel yük altındaki burkulma davranışlarını ve taşıma kapasitelerini deneysel olarak incelemeyi amaçlamaktadır. Araştırma kapsamında, 1.75 mm ile 3 mm arasında değişen et kalınlıklarına sahip 11 adet omega kolon numunesi, farklı kalınlıktaki dalgalı silo duvarı levhalarıyla birleştirilerek eksenel basınç testlerine tabi tutulmuştur. Deneyler, yanal destek koşullarının ve kolon et kalınlığının yük taşıma kapasitesi, elastik ötesi davranış ve göçme modları üzerindeki etkilerini analiz etmek üzere kurgulanmıştır. Elde edilen bulgular, omega kesitlerin silo duvarı gibi ikincil elemanlarla etkileşimli çalışma performansını ortaya koyarak literatürdeki önemli bir boşluğu doldurmaktadır. Çalışma, ince cidarlı bu elemanların modern inşaat uygulamalarındaki tasarımı için kritik veriler sunmaktadır.

Anahtar kelimeler: Soğukta şekil verilmiş çelik, Kolon, Deneysel çalışma, Omega kesit, Oluklu duvar

1 Introduction

Cold-formed steel (CFS) members are commonly used in today's construction industry, especially in steel silos, light steel structures, and storage rack systems. This popularity is due to their high strength-to-weight ratio, easy fabrication, and various cross-sectional shapes. In the design of these CFS column members, calculation methods recommended by the American AISI S100 [1], and European EN 1993 [2] standards are commonly utilized. Because they have thin walls, the structural behavior of these members is very sensitive to local, distortional, and global buckling modes, as well as to the complex interactions among them. In systems such as silo walls, where there are high lateral pressures and loads, the stiffness of the web and flange of the vertical load-bearing members, which act as columns, directly affects overall structural performance. In industrial settings, omega (Ω) sections are often chosen alongside standard lipped C- and U-sections, particularly when high stiffness is required. However, in composite setups where omega-section columns are externally supported by secondary components such as cladding or silo walls, the effect of lateral restraint conditions on the axial load capacity and failure modes of the columns remains poorly understood in the existing literature. Existing research in literature can be categorized into two primary axes: silo columns and isolated (normal) columns.

Silo columns exhibit unique structural behavior due to their continuous interaction with corrugated wall sheets. Sondej et al. [3] performed a critical evaluation of the Eurocode approach for cylindrical metal silos with corrugated walls and vertical stiffeners, noting that current standard formulas contain discontinuities and provide highly conservative results compared to linear buckling analysis (LBA). Wójcik et al. [4] conducted 3D buckling analyses of cylindrical metal bins, modeling how corrugated sheets provide complex lateral support to vertical stiffeners and investigating the significant influence of bulk solid stiffness on overall stability. Rejowski et al. [5] contributed vital experimental data by testing individual column buckling within real-scale silos in both empty and wheat-filled conditions. Their study demonstrated that the stored bulk material increases the column's buckling resistance by 20% to 45%, a capacity gain not fully reflected in current design codes

Research on isolated columns focuses on the interaction between section geometry, material properties, and various buckling modes. Khan et al. [6] investigated the buckling

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behavior of CFS omega (ω) sections under axial compression, numerically and experimentally validating that critical buckling loads increase directly with sheet thickness. Young and Rasmussen [7] studied the impact of fixed and pinned end conditions on singly symmetric columns, demonstrating that support conditions significantly influence the shift of the internal force's line of action following local buckling.

Wang et al. [8] tested complex channel sections with web and edge stiffeners, observing that Σ-shaped geometries can enhance load-carrying capacity by up to 65%, although failure becomes dominated by distortional buckling. Kwon et al. [9] examined the interaction between local and distortional buckling in high-strength steel channels, proposing refined design curves for the Direct Strength Method (DSM). Young [10] focused on the design of channel columns with inclined edge stiffeners, providing numerical and experimental analysis for fixed-ended specimens. Mitsui et al. [11] developed new energy-based functions for elastic critical local buckling, specifically accounting for plate element interactions at cross-section junctures.

Santos et al. [12] and Dinis et al. [13] investigated the triple interaction of local, distortional, and global (L-D-G) buckling modes in lipped channels, identifying that this complex coupling leads to a significant "erosion" of the column's ultimate strength. Wang et al. [14] explored Q460 high-strength steel columns, analyzing the law of influence that slenderness ratios have on buckling mode transitions. Ye et al. [15] conducted experiments on local-flexural interactive buckling, comparing results with Eurocode 3 and DSM to assess their accuracy across various cross-sections. Cava et al. [16] identified the most detrimental initial geometric imperfection shapes for columns experiencing L-D-G interaction using Koiter's asymptotic method and Monte Carlo simulations.

Kherbouche and Megnounif [17] proposed an improved DSM approach (DSM-t) for built-up open and closed section columns, utilizing the thickness at the web contact area to better represent composite action. Martins et al. [18] analyzed flange-triggered local-distortional interaction in web-stiffened lipped channels, evaluating the validity of existing design methods for these complex sections. Finally, Leng et al. [19] utilized genetic algorithms and steepest descent methods for shape optimization, showing that innovative geometries can achieve performance levels up to 26% higher than traditional designs.

A review of the current literature reveals that most studies have focused on standard open sections, such as C, U, and Z sections, or built-up closed sections. The complex composite action created when an omega column is bolted to a corrugated sheet, acting as both a load-bearing member and a lateral brace, remains poorly understood. This study addresses this void by experimentally investigating the buckling behavior and load-carrying capacities of cold-formed steel omega-section columns under axial compression. To achieve this, a total of 11 omega-section column specimens, with thicknesses ranging from 1.75 to 3.00 mm, were manufactured and tested under axial compressive loading. Furthermore, to accurately represent the lateral restraint conditions and overall system behavior observed in real silo applications, corrugated steel sheets ranging from 1.00 to 4.00 mm in thickness, mimicking silo walls, were attached to the side surfaces of the specimens. This series of tests thoroughly examines how varying the thicknesses of both the columns and the lateral restraining wall elements influences the load-carrying capacities, post-elastic behavior, and transitions between buckling modes of the omega-section columns.

2 Materials and methods

2.1 Test member

A total of 11 experimental tests were conducted to determine the axial compression capacities of cold-formed steel omega-section column specimens. The cross-sectional geometry investigated in the experimental program is presented in Figure 1, while the cross-sectional dimensions of the specimens are given in Table 1.

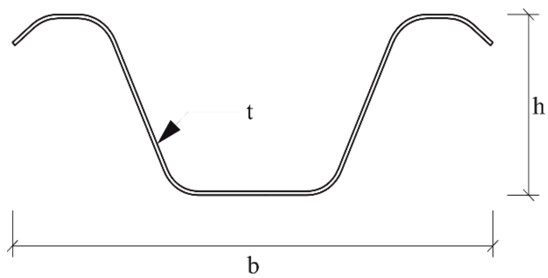


Figure 1. Cross-section of omega

Table 1. Cross-sectional properties of the members

Test members	b	h	t
K_1.75	230	80	1.75
K_2.00	230	80	2
K_3.00	230	80	3

Within the experimental program, the thickness of the column specimens ranged from 1.75 mm to 3.00 mm. A corrugated silo wall segment of varying thickness was attached to the column members. The corrugated profile for the silo wall had a depth of 15 mm and a corrugation width of 78 mm. This corrugated sheet was connected to the column with M20 bolts placed at 78 mm intervals. Detailed technical drawings of the test specimens are shown in Figure 2. To ensure composite action between the column and the silo wall segment during loading, the bottom and top ends of the specimens were covered with 5 mm-thick steel plates. This maintained the integrity of the sections. The tests used a hydraulic testing machine with a 600 kN capacity at a loading rate of 0.01 mm/s. During loading, vertical displacement measurements were taken at the top actuator.

2.2 Material tests

The test specimens were fabricated from DX51D grade hot-dip galvanized steel sheets. To determine the material's mechanical properties, tensile tests were conducted in accordance with EN ISO 6892-1 [14]. The specimen geometry used in the tensile tests is shown in Figure 3. All tensile tests were performed using a 600 kN universal testing machine at a controlled displacement rate of 0.01 mm/s. An extensometer with a gauge length of 100 mm was used to measure strain during testing accurately. The stress–strain curve obtained from the 1.75 mm, 2 mm and 3 mm thick specimens is presented in Figure 4. The key mechanical properties derived from these tests are summarized in Table 2.

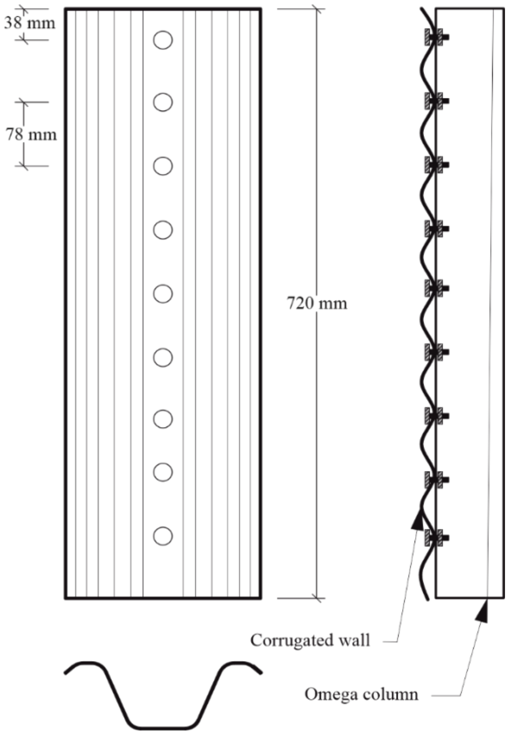


Figure 2. Test members

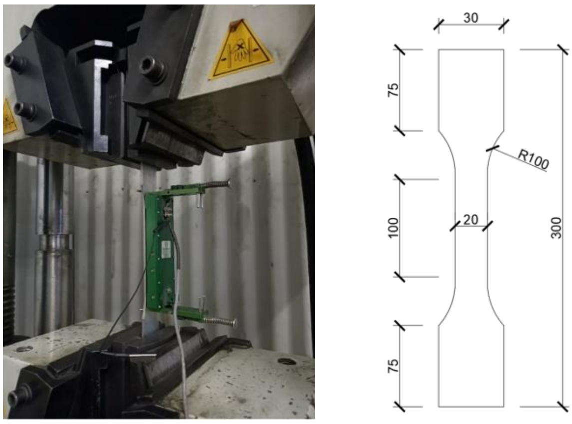


Figure 3. Tensile test details

3 Results and discussions

Within the scope of the experimental study, the axial compression behavior of cold-formed steel omega-section column specimens and their interaction with corrugated silo wall segments were investigated. The results obtained from a total of 11 tested specimens clearly demonstrate the influence of column thickness (1.75 mm, 2.00 mm, and 3.00 mm) and the varying thicknesses of the attached lateral restraint walls on the load-carrying capacity (Table 3).

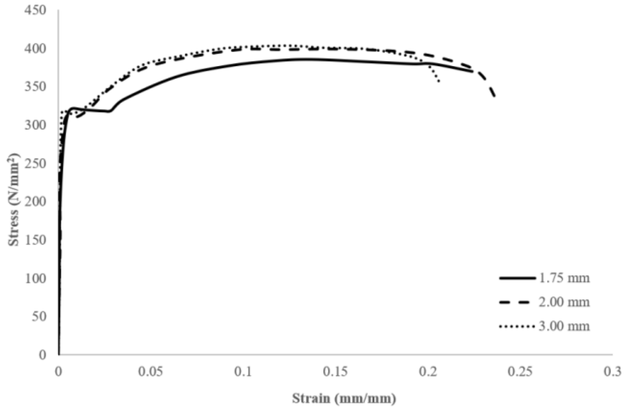


Figure 4. Tensile test results

Table 2. Mechanical properties

Test specimen	σ_{y0} (MPa)	E (MPa)	σ_u	ε_u
1.75 mm	294.27	203440	385.6	0.13
2.00 mm	309.49	202702	397.2	0.15
2.00 mm	316.4	205161	402.8	0.12

Table 3. Test results

Test specimen	Column thickness (mm)	Wall thickness (mm)	Load capacity (kN)
K_1.75/D_0	1.75	0	138
K_1.75/D_1.0	1.75	1.00	131
K_1.75/D_3.0	1.75	3.00	167
K_2.00/D_0	2.00	0	172
K_2.00/D_2.0	2.00	2.00	187
K_2.00/D_3.0	2.00	3.00	186
K_2.00/D_4.0	2.00	4.00	224
K_3.00/D_0	3.00	0	332
K_3.00/D_2.0	3.00	2.00	298
K_3.00/D_3.0	3.00	3.00	334
K_3.00/D_4.0	3.00	4.00	282

In the first stage of the experimental program, we looked at how well slender cold-formed steel omega columns with a thickness of 1.75 mm performed. The reference specimen in this group, K_1.75/D_0, which did not have any corrugated silo wall, showed an axial load-carrying capacity of 138 kN. For the K_1.75/D_1.0 specimen, where a thin corrugated wall segment with a thickness of 1.00 mm was attached to the main column, there was a slight drop in load-carrying capacity, with the ultimate strength reduced to 131 kN. This behavior suggests that the added thin-walled panel did not provide enough lateral stiffness to stop the main column from buckling. Also, possible eccentricity effects at the connection points may have hurt overall resistance. On the other hand, when we connected a much stiffer corrugated wall segment with a thickness of 3.00 mm to the same column section (specimen K_1.75/D_3.0), the load-carrying capacity increased significantly to 167 kN. This result shows that lateral restraint elements with enough thickness and buckling resistance can directly and positively improve the load-carrying performance of thin-walled primary members. Furthermore, it was observed that the critical buckling load and cross-sectional stiffness increased as the wall thickness increased. Specifically, the critical buckling load was seen to rise from the 90 kN level to 110 kN. (Figure 5).

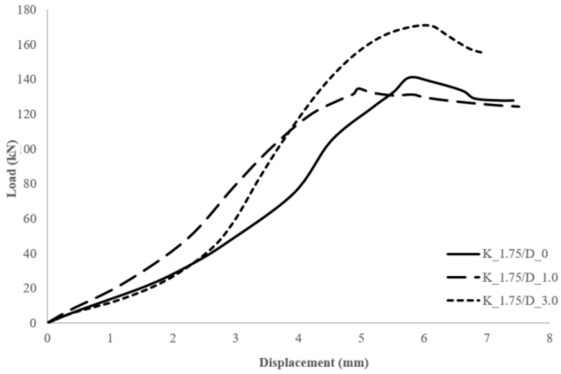


Figure 5. Load–displacement curves of 1.75 mm column thickness specimens with respect to wall thickness

In the second part of the study, cases in which the column thickness was increased to 2.00 mm were analyzed. The unbraced reference specimen, K_2.00/D_0, exhibited an axial load-carrying capacity of 172 kN. When a 2.00 mm thick corrugated wall was attached to the system (K_2.00/D_2.0), the capacity increased to 187 kN, while a similar strength of 186 kN was obtained with a 3.00 mm thick wall (K_2.00/D_3.0). This indicates that the effect of lateral restraint may reach a plateau within a range of wall thicknesses, resulting in comparable structural responses. However, in the K_2.00/D_4.0 specimen, where the wall thickness was increased to 4.00 mm, the system's load-carrying capacity increased significantly, reaching a peak of 224 kN. This maximum value clearly demonstrates that 2.00 mm-thick columns, when supported by substantially stiffer and thicker (4.00 mm) corrugated wall elements, achieve improved structural integrity and maximize load-carrying capacity. The critical buckling load was seen to rise from the 115 kN level to 145 kN (Figure 6).

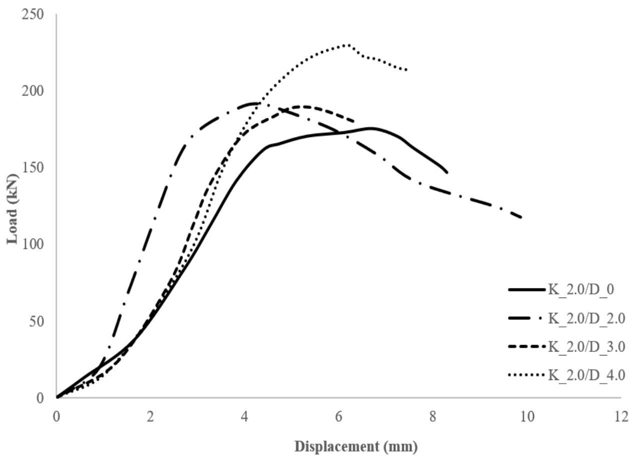


Figure 6. Load–displacement curves of 2 mm column thickness specimens with respect to wall thickness

When examining the final group of specimens with a column thickness of 3.00 mm, a different structural mechanism emerged compared to the thinner column groups. The reference specimen in this group, K_3.00/D_0, which had no silo wall, showed the highest performance among all unbraced reference columns, reaching a load-carrying capacity of 332 kN. However, when a 2.00 mm thick corrugated wall was added to this rigid main column (K_3.00/D_2.0), the capacity decreased to 298 kN. A similar result was seen with the K_3.00/D_3.0 specimen, which reached 334 kN, closely resembling the reference case. In contrast, when the wall thickness increased to 4.00 mm (K_3.00/D_4.0), the load-carrying capacity again dropped, reaching 282 kN. These changes are especially noteworthy. The 3.00 mm thick columns already have a high moment of inertia and strong buckling resistance. Thus, the added corrugated wall elements did not improve overall system stability. Instead, the eccentricities from single-sided bolted connections and localized interface stress appeared to degrade structural performance. This led to early buckling or failure, limiting load-carrying capacity rather than enhancing it (Figure 7)

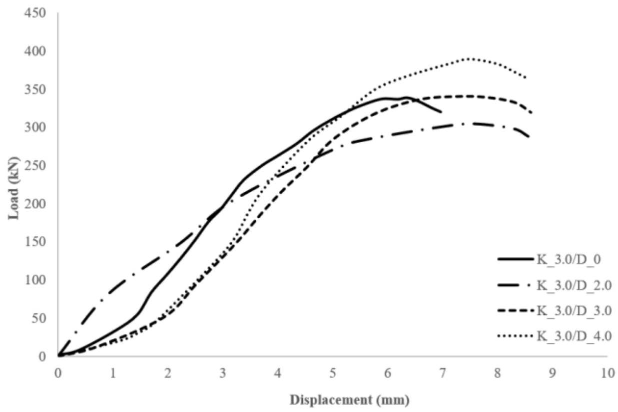
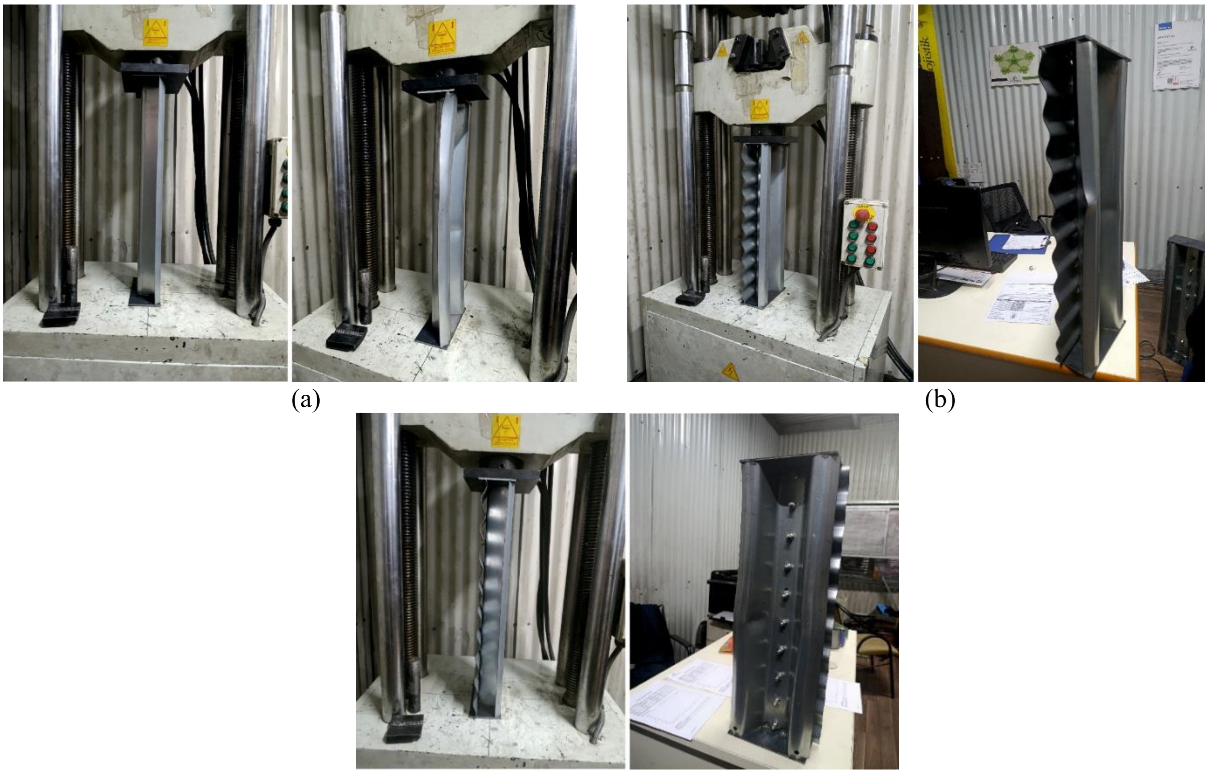


Figure 7. Load–displacement curves of 3 mm column thickness specimens with respect to wall thickness

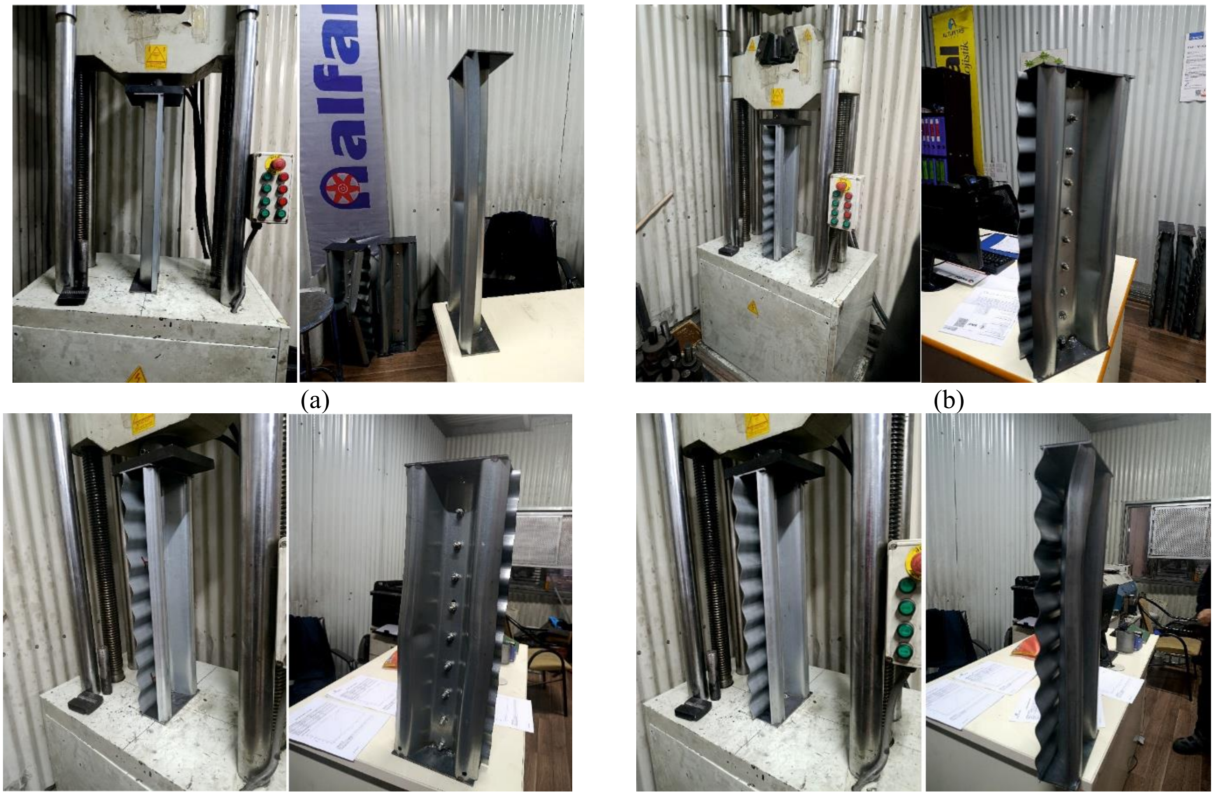
The enhancement of the axial load-carrying capacity of cold-formed steel omega columns through lateral restraint depends strongly on the ratio between the column wall thickness and the thickness of the corrugated supporting wall. While rigid wall integrations significantly improve the capacity of slender columns with thicknesses of 1.75 mm and 2.00 mm, no clear structural benefit is observed for relatively thick and already stiff columns with a thickness of 3.00 mm. In fact, for these stockier members, the addition of lateral wall elements may even reduce capacity due to eccentricity effects introduced by bolted connections.

The post-test deformed shapes of the specimens are presented in Figures 8–10. Examination of the failure modes indicates that for columns with thicknesses of 175 mm and 2.00 mm, failure was governed by local buckling leading to overall elastic instability. In contrast, for 3.00 mm thick columns, the failure mode was characterized as an interactive failure mode dominated by local buckling and end crushing, rather than a purely global buckling mode. For wall-supported columns, however, deformation patterns showed that failure occurred without global buckling; instead, localized crushing near the supports was observed following local buckling.



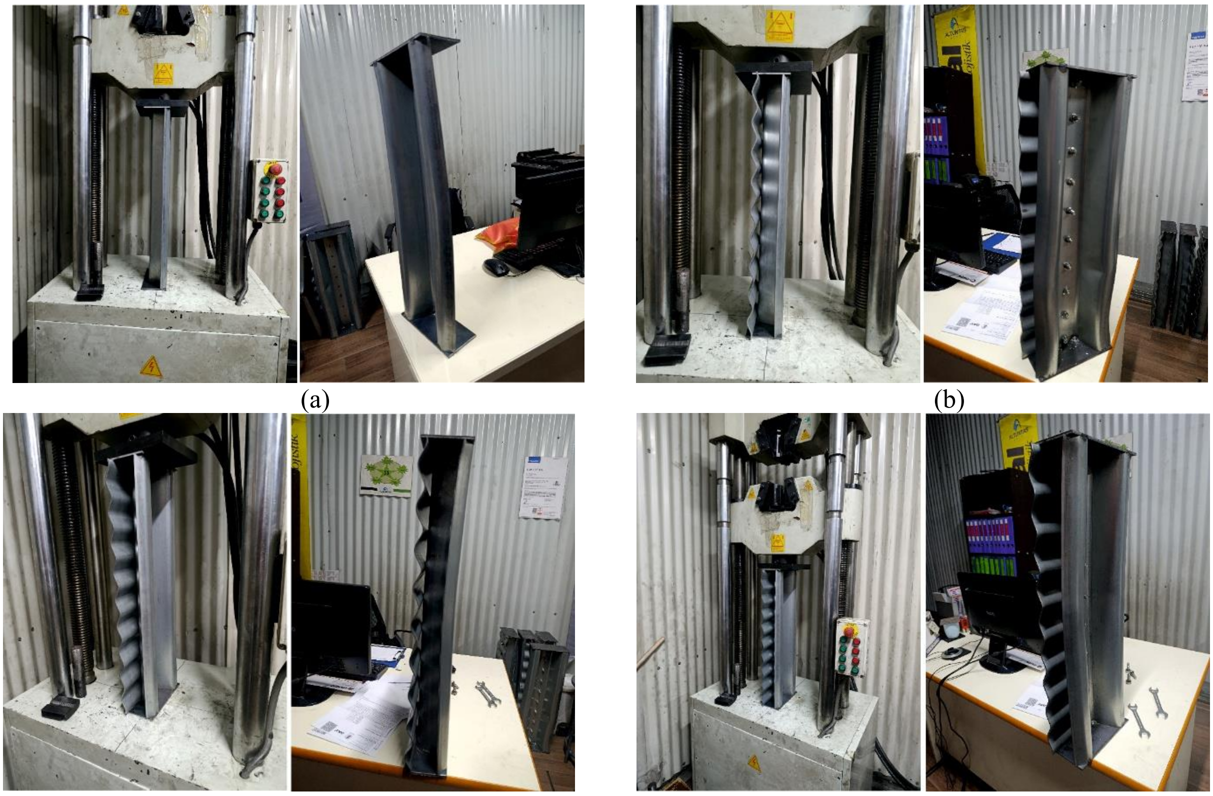
(a) (b) (c)

Figure. 8. Test members with a thickness of 1.75 mm and their deformation patterns (a) K_1.75/D_0, (b) K_1.75/D_1.0, (c) K_1.75/D_3.0



(a) (b) (c) (d)

Figure. 9. Test members with a thickness of 2 mm and their deformation patterns (a) K_2.00/D_0, (b) K_2.00/D_2.0, (c) K_2.00/D_3.0, (d) K_2.00/D_4.0



(a) (b) (c) (d)

Figure. 10. Test members with a thickness of 3 mm and their deformation patterns (a) K_3.00/D_0, (b) K_3.00/D_2.0, (c) K_3.00/D_3.0, (d) K_3.00/D_4.0

4 Conclusions

In this study, the buckling behavior and load-carrying capacity of cold-formed steel omega (Ω) section columns, widely used as vertical load-bearing elements in steel silos and industrial light steel structures, were experimentally investigated under axial compression. Unlike conventional studies reported in the literature, the present work specifically considers omega-section columns continuously supported on their outer surfaces by corrugated steel sheets (representing silo walls). Based on axial compression tests conducted on 11 different specimens, the following key conclusions can be drawn:

The continuous attachment of corrugated steel sheets representing silo walls to omega-section columns using M20 bolts at 78 mm spacing significantly enhanced the columns' lateral stiffness and improved their resistance to global buckling. This composite interaction condition ensured compatible deformation between the column and the wall under axial loading, thereby contributing to a pronounced increase in load-carrying capacity.

The lateral restraint points provided by the corrugated sheets delayed the initiation and progression of local and distortional buckling modes, which are characteristic failure mechanisms of thin-walled members. Increasing the thickness of the silo wall elements from 1 mm to 4 mm further restricted the development of buckling waves in the web and flange regions, thereby mitigating complex mode interactions.

It was observed that the interaction between column and wall thicknesses decisively influenced structural performance, with load-carrying capacity increases occurring only at certain thickness ratios. While lateral restraint provided by the walls generally enhanced the strength of 1.75 mm and 2.00 mm columns when supported by sufficiently thick walls, it led to a capacity reduction in 3.00 mm columns due to the introduction of eccentricities at bolted connection points. As the section thickness increased, the influence of local buckling generally decreased, the effective utilization of post-elastic reserve capacity increased, and the members exhibited more stable behavior up to failure.

In conclusion, the combined interaction between omega-section columns and corrugated steel cladding represents a critical parameter governing the structural resistance of industrial steel silos. The comprehensive experimental database developed in this study provides a robust basis for future finite element analyses (FEA) and parametric numerical investigations, as well as for the calibration and validation of advanced design approaches.

The findings of the present study indicate that several promising research directions exist for a more comprehensive understanding of the behavior of cold-formed steel (CFS) omega-section columns, as well as for integrating these results into design practice. First, based on the experimentally obtained load–displacement responses and observed failure modes, validated nonlinear finite element models can be developed using software such as

Abaqus. Once these models are verified against experimental data, they can be extended to parametric studies considering different steel grades (such as DX51), a range of thicknesses, and varying column lengths. Such studies would significantly expand the available database in the literature.

In addition, a more detailed understanding of the interaction between local, distortional, and global buckling modes under lateral restraint conditions can be achieved through finite strip analyses using tools such as CUFSM. This would help clarify the role of lateral support in modifying the buckling behavior of thin-walled omega sections. Furthermore, the influence of connection details used in attaching corrugated steel sheets to the columns, including bolt spacing, bolt diameter, and alternative joint configurations such as lapped or sleeved connections, should be systematically investigated through both experimental and numerical approaches, as these parameters may have a direct effect on overall system stiffness and strength.

It is also important to extend the scope of future studies beyond pure axial compression in order to better represent real silo conditions. In this context, the behavior of omega-section columns under combined axial load and bending moment, particularly those induced by wind and seismic actions, should be examined. Finally, the extensive experimental and numerical data obtained from such studies should be used to develop improved and more realistic design expressions within the framework of AISI S100 and the Direct Strength Method. Incorporating the effect of lateral restraint into these formulations is expected to lead to more economical and reliable design approaches for practical engineering applications.

CRediT authorship contribution statement

Ramazan Oruç: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing–original draft, Writing–review and editing; **Yakup Bölükbaş:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft, Writing–review and editing, **Mehmet Emin Kara:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology

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Conflict of interest

The authors declare that they have no conflict of interest.

Similarity rate (Turnitin): %17

Declaration of generative artificial intelligence (AI) and AI-assisted technologies in the writing process

During the preparation of this work, the authors used the Gemini Notebook application to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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