

Nonlinear Response and Stability Assessment of Discretely Supported Steel Silos with Variable Plate Thickness under Dynamic Loading

Chitrekhya, Shiva Verma, Akhand Pratap Singh, Parmeshwar Sahu

P.G. Student, Department of Civil Engineering, Shri Rawatpura Sarkar University, Raipur, India

Assistant Professor, Department of Civil Engineering, Shri Rawatpura Sarkar University, Raipur, India

Assistant Professor, Department of Civil Engineering, Shri Rawatpura Sarkar University, Raipur, India

Assistant Professor, Department of Civil Engineering, Shri Rawatpura Sarkar University, Raipur, India

ABSTRACT: The Thin-walled shell structures such as cylindrical, conical, hemispherical, and elliptical forms are widely used in engineering applications due to their structural efficiency and material economy. However, these systems are highly susceptible to instability phenomena, particularly buckling under external pressure and complex loading conditions. Among these, cylindrical steel silos represent critical slender shell structures extensively utilized for the storage of bulk materials including cement, grain, fly ash, soot, and coal dust. Their operational demands expose them to highly variable loading scenarios, ranging from moderate to extremely high magnitudes, which often result in unconventional stress distributions and failure mechanisms. This study aims to enhance the current understanding of the structural behavior, strength, and buckling characteristics of steel silos, with particular emphasis on silos supported on discrete individual supports. A comprehensive analytical investigation has been conducted based on established literature, incorporating variations in shear wall curvature to evaluate their influence on structural performance. The dynamic response of the silo structures has been assessed using Response Spectrum Analysis, implemented through the finite element software STAAD.Pro. The research presents a comparative evaluation of different silo configurations under lateral loading conditions, highlighting the impact of geometric variations and modeling approaches on structural stability. The findings contribute to identifying optimized design configurations and provide practical guidance for the safe and efficient design of future steel silo structures. Additionally, the study outlines key areas requiring further investigation to advance the reliability and performance of such critical storage systems.

KEYWORDS: Steel silos; Thin-walled shell structures; Buckling analysis; Structural instability; Response Spectrum Analysis; STAAD.Pro; Lateral load behavior; Shear wall curvature; Dynamic analysis; Finite element modeling; Structural optimization; Collapse mechanisms.

I. INTRODUCTION

The Bulk material storage systems are commonly categorized as bins, bunkers, silos, or tanks, although universally accepted distinctions among these terms are limited. In general, shallow storage units used for materials such as coal, ore, crushed stone, and gravel are referred to as bins or bunkers, whereas taller storage systems designed for materials like grain and cement are typically classified as silos. In this study, the term silo is used in a generalized sense to represent steel structures employed for bulk material storage. Steel silos offer several advantages over conventional storage systems, particularly those constructed from reinforced concrete. Due to their lightweight nature, steel silos can be rapidly fabricated, assembled, and dismantled. They exhibit flexible structural behavior, allowing reversible deformations under uneven or transient loading conditions. Additionally, their reduced self-weight results in lower foundation loads, making them economically and structurally efficient. These characteristics have led to their widespread adoption across multiple industries, including mining, agriculture, chemical processing, power generation, and food production. Most steel silos are circular in plan and may be constructed either as ground-supported or elevated structures. A typical silo consists of a cylindrical shell, a conical hopper for material discharge, and a roof structure. The junction between the cylindrical shell and the hopper, commonly referred to as the transition zone, is often reinforced with a stiffening ring to ensure structural continuity. Support conditions vary significantly in practice, with discrete supports such as columns frequently used. These supports may terminate below the transition zone, extend to

the roof level, or partially engage with the shell. In this study, discretely supported silos are defined as those in which the cylindrical shell is supported directly by localized supports of specified width.

1.1 Suitability of Steel Structures

Steel structures are widely preferred in industrial applications due to their high strength-to-weight ratio, durability, and adaptability. Industrial buildings often require large unobstructed spaces to accommodate machinery, cranes, and storage systems, making steel an ideal construction material. Advances in fabrication technology and standardized design practices have further enhanced the efficiency and cost-effectiveness of steel construction. The dynamic behavior of steel structures, however, requires careful consideration, especially under external hazards such as wind and seismic loading. Steel structures are particularly sensitive to dynamic excitation due to their relatively low mass and high flexibility. Nevertheless, their ease of fabrication, rapid erection, recyclability, and potential for future modification make them highly sustainable. Modern steel construction integrates advanced tools for analysis, design, detailing, and manufacturing, enabling optimized and reliable structural performance.

1.2 Loads Acting on Silos

Silos are subjected to a combination of static and dynamic loads arising from stored materials and environmental effects. According to relevant design standards such as IS 875 (Part I–V), the primary loads to be considered include:

- Self-weight of the structural components
- Stored material load
- Roof and floor loads
- Wind loads
- Imposed loads and deformation effects

The interaction of these loads often leads to complex stress distributions within the silo structure.

1.3 Failure Modes in Steel Silos

Due to their thin-walled configuration and exposure to varying load conditions, steel silos are prone to several modes of failure. Structural instability is often governed by critical stress states in the shell. Common failure modes include:

For cylindrical shells:

- Buckling under axial compression
- Circumferential (hoop) buckling
- Shear buckling of the shell membrane
- Localized failure near support regions

For conical hoppers and transition zones:

- Collapse or yielding of the hopper shell
- Failure at hopper-to-shell connections
- Buckling or plastic collapse of transition rings
- Local failure at discrete supports

These failure mechanisms highlight the importance of detailed structural analysis and careful design.

1.4 Earthquake Effects on Silo Structures

Seismic loading has been identified as a critical factor influencing the performance and safety of silo structures. Historical earthquake events have demonstrated that silos are particularly vulnerable to damage and collapse, often resulting in significant economic losses and safety hazards. Earthquake ground motion consists of three components, generating both vertical and horizontal forces. While vertical seismic effects are generally less significant for heavy silo systems, horizontal forces play a dominant role, especially in tall and slender structures. The magnitude of lateral seismic forces is proportional to the mass of the silo and its contents. As the height of the silo increases, the center of mass rises, leading to larger overturning moments at the base. Additionally, dynamic interaction between the stored material and the silo structure can amplify internal stresses. Material movement during seismic excitation may cause impact loads and uneven pressure distribution, further increasing the risk of structural failure. Therefore, accurate dynamic analysis is essential for evaluating seismic performance and ensuring the safety of silo structures.

II. LITERATURE SURVEY

Ground Rotter (1990) conducted a detailed investigation on the elastic–plastic collapse of axially compressed and internally pressurized thin cylindrical shells near support regions. The study highlighted the occurrence of the well-known “elephant’s foot” buckling mode, which is critical in the design of storage structures such as silos, bins, and tanks. A simplified design equation was proposed, improving upon earlier empirical formulations.

Alauddin and Ahmad (1995) performed full-scale analyses of circular silos with varying support configurations subjected to multiple loading conditions. Their findings indicated that conventional design approaches often fail to accurately predict stress resultants, emphasizing the need for more refined analytical methods.

Teng (1997) examined the plastic buckling behavior of ring beams located at the transition zone between the cylindrical shell and conical hopper. The study identified out-of-plane buckling as a dominant failure mode due to circumferential compressive forces and proposed a simplified plastic buckling model suitable for design applications.

Croll (2006) investigated nonlinear elastic–plastic buckling of thin cylindrical shells under combined internal pressure and axial compression. The research demonstrated that axisymmetric local buckling modes are highly influenced by boundary and support conditions, and presented an analytical framework to predict such failures.

Bischoff (2008) focused on three-dimensional shell analysis using different finite element formulations, including shell and solid elements. The study compared numerical performance with theoretical models and highlighted challenges such as locking effects, which significantly influence the accuracy of thin shell simulations.

Dash and Raju (2008) analyzed the buckling behavior of composite cylindrical shells with reinforced cut-outs using finite element methods. Their results showed that cut-outs lead to stress concentration and increased deformation, while proper reinforcement can enhance the overall buckling strength.

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III. METHODOLOGY

The present study adopts a systematic analytical approach to evaluate the structural behavior of steel silos under various loading conditions. The methodology integrates data collection, numerical modeling, and advanced structural analysis using finite element techniques to ensure accurate assessment and comparison of different silo configurations.

3.1 Methodological Framework

The overall procedure followed in this study consists of the following sequential steps:

Data Collection: Relevant geometric, material, and loading parameters of steel silos are obtained from established literature and design standards.

Model Development: Three-dimensional finite element models of silo structures are generated based on the collected data. Geometry

Definition and Property Assignment: Structural geometry is defined, and appropriate material properties, section properties, and thickness parameters are assigned.

Boundary Condition and Load Application: Realistic support conditions are incorporated, and loads such as self-weight, stored material load, wind load, and seismic load are applied.

Analysis Execution: Suitable analysis methods are selected, and simulations are carried out using structural analysis software.

Result Interpretation: Output results are extracted, compared, and critically evaluated to understand structural performance.

Validation and Comparison: The obtained results are compared with existing design approaches and previously reported studies to assess accuracy and reliability.

3.2 Modeling and Analysis Using STAAD.Pro

The structural modeling and analysis in this study are performed using STAAD.Pro, a widely used finite element software for structural engineering applications. Two primary approaches are available for modeling:

Command File Method: Involves manual input of model data through text-based commands, allowing precise control over modeling parameters. **Graphical User Interface (GUI) Method:** Provides a visual environment for creating and modifying structural models, improving efficiency and usability. The analysis process within the software is broadly divided into the following stages:

1. Modeling

Development of the structural model including nodes, elements, geometry, and material definitions representing the steel silo configuration.

2. Loading

Application of all relevant loads, including gravity loads, material loads, wind forces, and seismic effects, in accordance with design standards.

3. Analysis Types

Different analysis techniques are employed to capture various structural behaviors:

Elastic Analysis: Assumes linear material behavior to evaluate basic stress and deformation response.

P-Delta Analysis: Considers geometric nonlinearity due to second-order effects, particularly important for slender structures such as silos.

Buckling Analysis: Determines the critical load at which structural instability occurs.

Cable Analysis: Used where flexible tension elements are involved, if applicable.

IV. RESULT EVALUATION

The results obtained from the analysis are interpreted using:

Tabular Outputs: Numerical data including displacements, stresses, and internal forces.

Graphical Visualization: Contour plots and deformation shapes for better understanding of structural behavior.

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TABLE3.1: Structural Properties of Steel Silo

Parameter	Description / Value	Unit
Silo Type	Cement Steel Silo	–
Capacity	100	tonne
Number of Supports	4	–
Support Level	2.2	m
Wall Thickness	10 – 40	mm
Total Height	11.5	m
Cylinder Diameter	1.6	m
Material Behavior	Isotropic & Elastic	–
Young’s Modulus	21000	MPa
Poisson’s Ratio	0.3	–
Mass Density	7800	kg/m ³

TABLE3.2: The loading on the structure is considered as per following calculations

Parameter	Value	Unit
Unit Weight of Iron Ore	37	kN/m ³
Diameter of Silo	7	m
Height of Cylindrical Portion (h ₁)	8.05	m
Height of Hopper Portion (h ₂)	3.5	m
Weight of Roof	18.5	kN
Column Diameter	500	mm
Stiffener Size	ISA 70 × 70 × 8	–
Horizontal Stiffener Spacing	1.1	m
Vertical Stiffener Spacing	0.88	m
Opening Size	500	mm
Weight of Lining	0.25	kN/m ²
Top Cover Load	4	kN/m ²
Equipment Load	15	kN
Chute Load	10	kN
Conveyor Load	5	kN
Unit Weight of Plate	0.628	kN/m ²

TABLE3.3: Earthquake load for the structure has been calculated as per IS-1893(Part 1):2002

Parameter	Value
Seismic Zone	II
Zone Factor (Z)	0.1
Response Reduction Factor (R)	4
Importance Factor (I)	1.5

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Soil Type	Medium
Damping Ratio	0.02

TABLE3.4: Wind load for the structure has been calculated as per IS 875 (part-3)

Parameter	Value	Unit
Wind Speed	6	km/h
Terrain Category	2	–
Structure Class	B	–
Risk Coefficient (k_1)	1	–
Topography Factor (k_3)	1	–

TABLE3.5: Temperature forces data

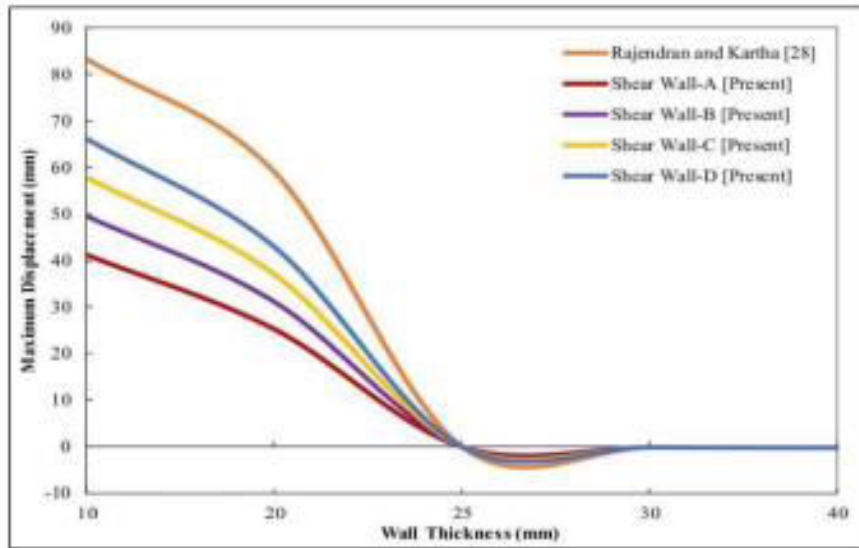
Parameter	Value	Unit
Coefficient of Thermal Expansion (α)	12×10^{-6}	/°C
Temperature Difference	20	°C

IV. EXPERIMENTAL RESULTS

4.1 MAXIMUM DISPLACEMENT

Table 4.1: Comparison of maximum displacement results for different type of structure

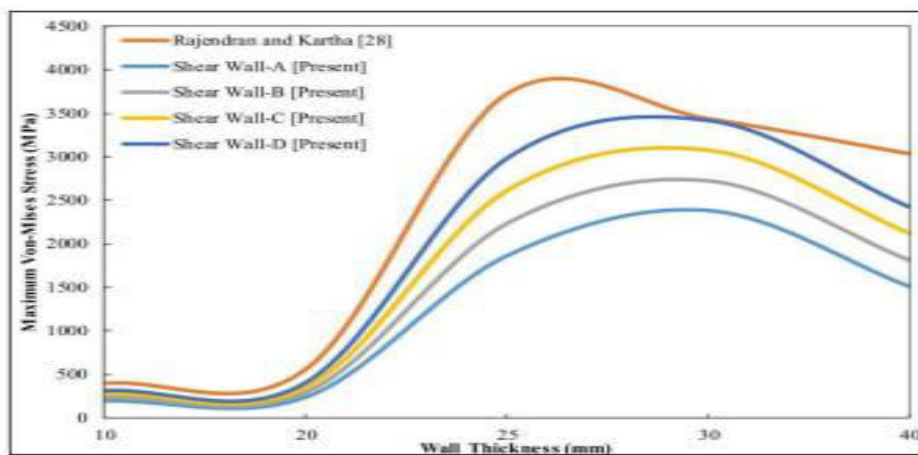
Thickness of Plate (mm)	Shear Wall A	Shear Wall B	Shear Wall C	Shear Wall D
10	41.3	49.65	57.992	66.336
20	25.3	31.22	37.132	43.046
25	0.012	0.015	0.0174	0.0199
30	-0.077	-0.088	-0.099	-0.11
40	-0.107	-0.129	-0.151	-0.172



4.2 MAXIMUM VON-MISES STRESS

Table 4.2: Comparison of maximum von-mises stress results for different type of structure

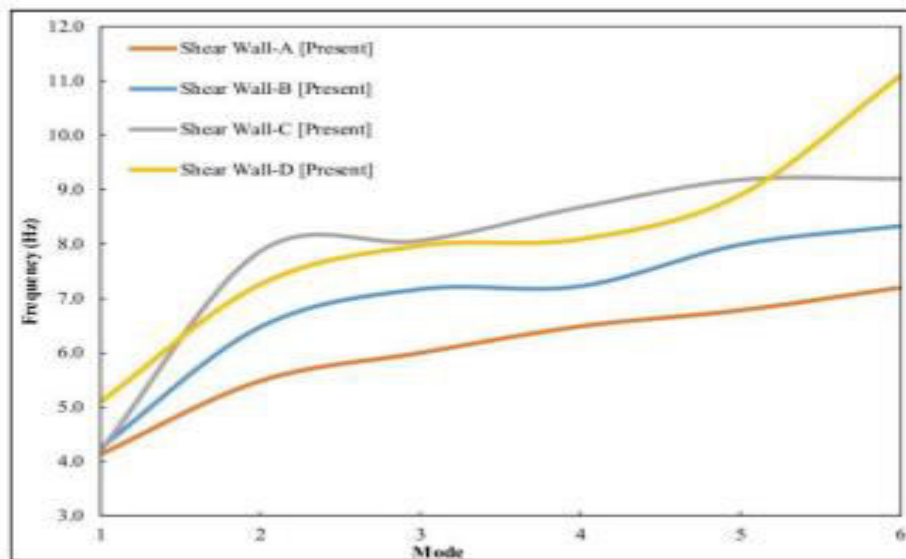
Thickness of Plate (mm)	Shear Wall A	Shear Wall B	Shear Wall C	Shear Wall D
10	195.1	234.5	273.95	313.37
20	238.5	294.3	350.03	405.78
25	1866	2239	2610.8	2982.9
30	2385	2728	3071.1	3414.2
40	1509	1812	2114.6	2417.6



4.3 FREQUENCY

Table 4.3: COMPARISON OF FREQUENCY (HZ) DUE TO SEISMIC ANALYSIS

Mode	Shear Wall A	Shear Wall B	Shear Wall C	Shear Wall D
1	4.13	4.25	4.19	5.09
2	5.48	6.47	7.87	7.26
3	5.99	7.17	8.07	7.97
4	6.48	7.22	8.68	8.09
5	6.77	7.98	9.19	8.9
6	7.187	8.323	9.208	11.085



V. CONCLUSION

The structural response of steel silo systems with varying plate thickness and shear wall configurations using finite element analysis. The results demonstrate a strong dependence of structural performance on both geometric parameters and support conditions.

From the thickness-based analysis, it is observed that the response of shear walls varies significantly with an increase in plate thickness. For lower thickness values (10–20 mm), relatively high response values are recorded, indicating reduced stiffness and higher deformation. As the thickness increases to intermediate levels (around 25 mm), the response approaches near-zero values in one dataset, suggesting a transition point where the structure achieves improved stability. However, further increase in thickness (30–40 mm) results in negative response values, indicating a possible shift in stress distribution or development of compressive effects within the system.

In contrast, the second dataset shows a substantial increase in response values with increasing thickness, particularly beyond 25 mm, where a sharp rise is observed (e.g., values exceeding 1800 and 2300 for different shear walls). This indicates that increasing stiffness does not always correspond to improved performance and may lead to higher force

attraction and stress concentration in certain configurations. Notably, the response consistently increases from Shear Wall A to Shear Wall D across all thicknesses, highlighting the influence of geometric positioning and load distribution.

The modal analysis further supports these findings, where natural frequencies increase progressively from Mode 1 to Mode 6 for all shear wall configurations. Shear Wall D consistently exhibits the highest modal values (reaching up to 11.085), indicating greater stiffness or reduced flexibility compared to the other configurations. This trend confirms that structural configuration significantly affects dynamic characteristics and seismic response behavior.

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