

RESEARCH ON A NEW DOUBLE-WALL STEEL INSULATION SILO WITH MULTIPLE BOLTED JOINTS: PART I, STRUCTURE SYSTEM

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ABSTRACT: The objective of this paper is to study a new double-wall steel insulation silo with multiple bolted joints for grain storage, which is designed to improve the insulation effect and mechanical behavior of the traditional silo structure. The silo employs the planar thin-walled steel plate as the internal wall, and the continuous ladder-shaped profiled plate as the external wall. The cavity between the internal and external walls is filled with insulation material. The silo utilizes specifically designed bolt connections to connect the internal and external walls. This paper carefully studied the structural behavior of the silo and the results indicate that the horizontal pressure from the grains is resisted by the internal wall under tension, and that the vertical friction force is mainly carried by both the external and internal walls. The stability of the internal wall is effectively provided by the external wall. The selection of connection model between the internal and external walls has a significant impact on the structural performance of the silo. To make the optimal selection, further verification and experimental studies are needed.

Keywords: Steel insulation silo; double-wall; multiple bolted joints; structural behavior; connection model between the internal and external walls

1. INTRODUCTION

There are two types of silos for grain storage, the reinforced concrete silos and the steel silos. The steel silos have been more widely applied due to their advantages such as light weight, low cost, short construction period, waterproof property, and outstanding impermeability.

The main loads on the steel silo structures are the horizontal pressure and the vertical friction force from the grains. Janssen[1] first proposed the formula to calculate horizontal pressure and vertical friction force at the end of the 19th century. The formula has been adopted by the standards of many countries (China [2], Australia [3], Europe [4], ISO [5], the United States [6] and so on). The horizontal pressure coefficient k in the formula has become an important research focus. Many studies and experiments demonstrated the dynamic effects of the horizontal pressure in the process of loading and unloading. Walker [7] and Zhong [8] conducted in-depth studies on dynamic unloading. However, no consensus on the mechanism of the dynamic pressure has been reached. The current studies mainly focus on single-layer thin-walled steel silos. Pincher [9], Teng [10], Sadowski [11] and Zhao [12] studied the stability and initial imperfection of silos. Teng [13], Laier [14], Dogangun [15] and Sadowski [16] studied the collapse behavior and the influence of eccentric load. However, few studies have focused on the steel insulation silo structure.

Most of the steel silos in use are single-layer and thin-walled, which leads to ill-function of the silos. The silo wall is so thin that a temperature difference between the inside and outside of the silo can easily form. Moisture condensation, imbalanced temperature distribution and high grain temperature are observed when the silo is greatly affected by the external environment. These bring a great threat to grain storage safety, to reduce which, the proper ventilation equipment should be installed and the frequency of the grain turnover should be increased. These countermeasures increase the costs and grain consumption.

The commonly used steel silos are constructed of corrugated steel plates and reinforcing ribs with bolted connections, from which some mechanical defects are usually observed. The shape of corrugated plate determines that it can bear only the horizontal pressure. The vertical loads are carried only by the reinforcing ribs. The restraint of the corrugated plate on the flexural buckling of the reinforcing rib is insignificant. The silo is very sensitive to the eccentric loads, which increases the instability of the silo, thus leading to a possible collapse.

In order to improve the insulation effect and mechanical behavior of the traditional silo structure, this paper proposes a double-wall steel insulation silo with multiple bolted joints for grain storage and carefully analyzes its structural behavior. This new silo has been granted patent [17].

2. SYSTEM INTRODUCTION

(1) Silo Structure

The double-wall steel insulation silo with multiple bolted joints proposed in this paper inherits the merits of the existing fabricated steel silo while having the capability of insulation. The silo employs the planar thin-walled steel plate as the internal wall, and the continuous ladder-shaped profiled plate as the external wall. The planar internal wall can effectively reduce the vertical friction force from the grains as well as the cleaning work. The silo utilizes specifically designed bolt connections to connect the internal and external walls. Vertically, several internal and external ring beams are set respectively for the internal and external walls. The section of the silo is shown in Figure 1 and the bolt connection set is shown in Figure 2.

(2) Insulation Principle

The cavity between the internal and external walls is filled with insulation material, which produces an outstanding insulation effect for the silo. Thermal insulation caps at the external side of the bolt connection sets are also employed to cut off the “thermal bridge”, thus further promoting the insulation performance of the silo. Sandwich panels are adopted for insulation and enclosure on the top of silo.

The silo is environmentally friendly, featured with simple structure and high integrity. The design of the silo enables it to save energy and steel consumption with a pleasant appearance. Each construction member can be prepared in factories to facilitate field installation with the “upside-down construction method”. A completed silo is shown in Figure 3.

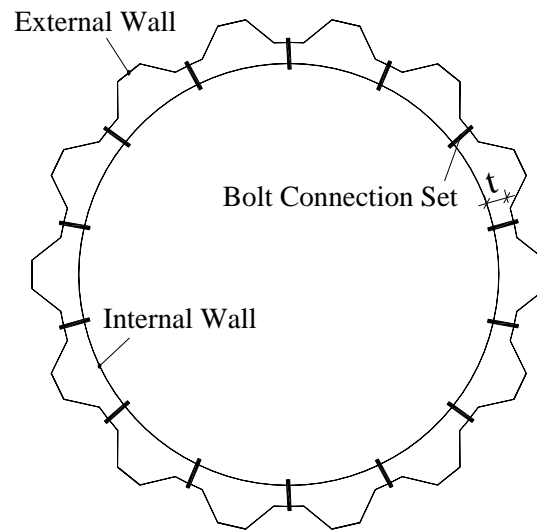


Figure 1. Section Form of the Double-wall Silo

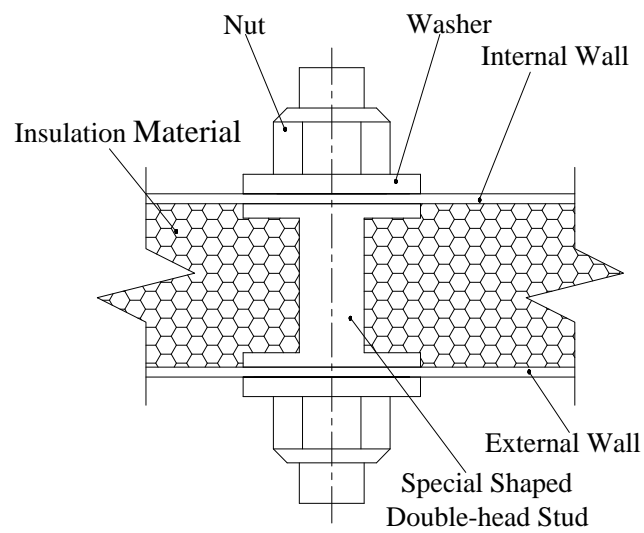


Figure 2. Diagram of Bolt Connection Sets

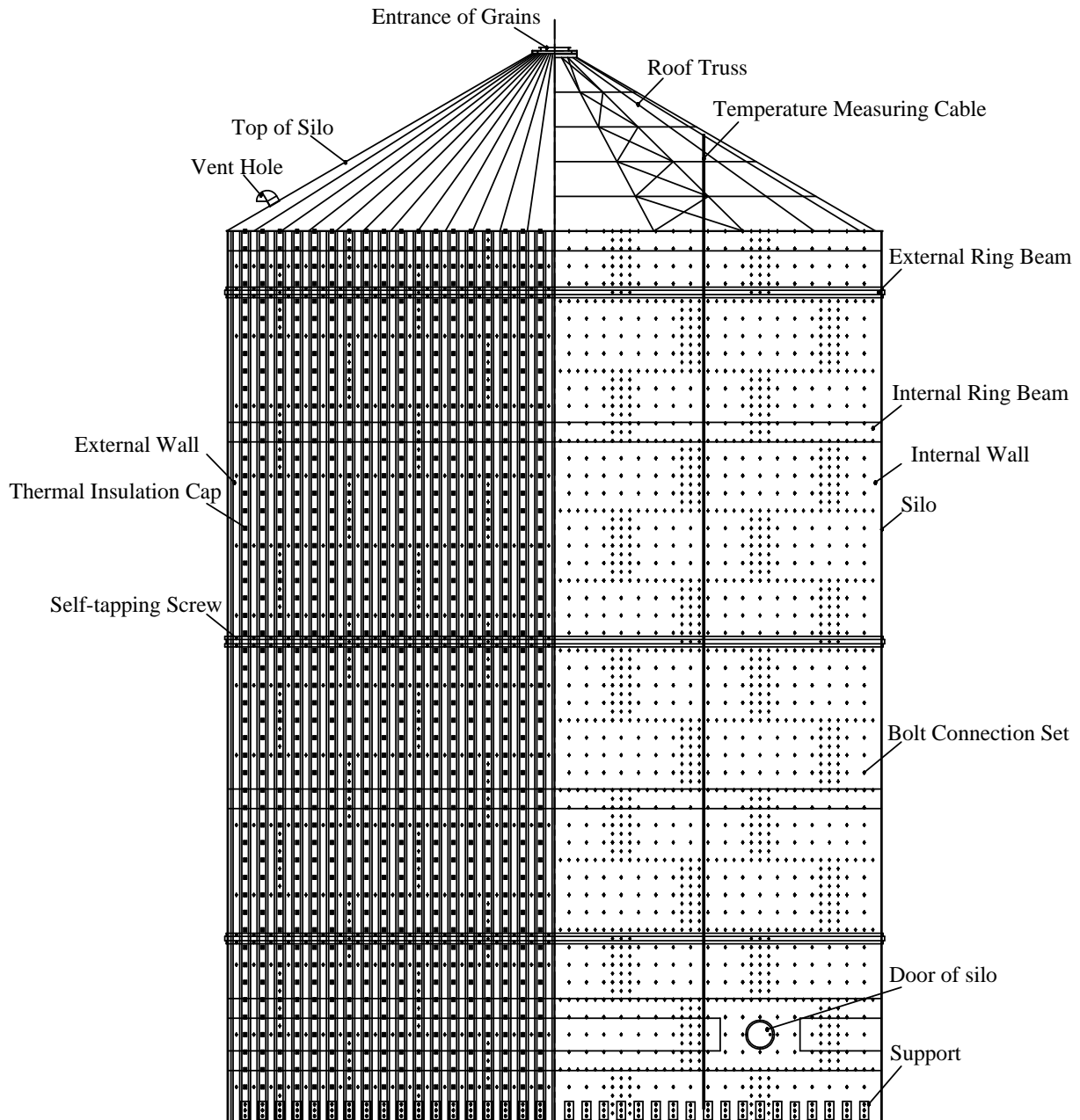


Figure 3. Double-wall Steel Insulation Silo with Multiple Bolted Joints

3. STRUCTURE PRINCIPLE

The internal and external walls cooperatively share the loads. The internal wall has a good tensile property, yet still unable to independently bear the large vertical pressure in the plane. Therefore, supports from other external construction members are needed. The external wall performs good bearing capacity along the vertical direction but little bearing capacity in the horizontal direction. A careful configuration and design of the double-head bolts can promote the cooperation between the internal and external walls.

The silo structure is axisymmetric, and its force diagram under grain loads is shown in Figure 4. The horizontal pressure from the grains is resisted by the internal wall under tension; the external wall helps carry the vertical friction force and provides effective supports to the stability of the internal wall.

In addition, the internal and external ring beams can promote the mechanical behavior and stability of the silo. The external and internal walls together resist the wind, snow, and earthquake loads. The roof truss serves as a restraint on the whole top area of the silo walls and delivers the loads on the top of silo to the silo walls.

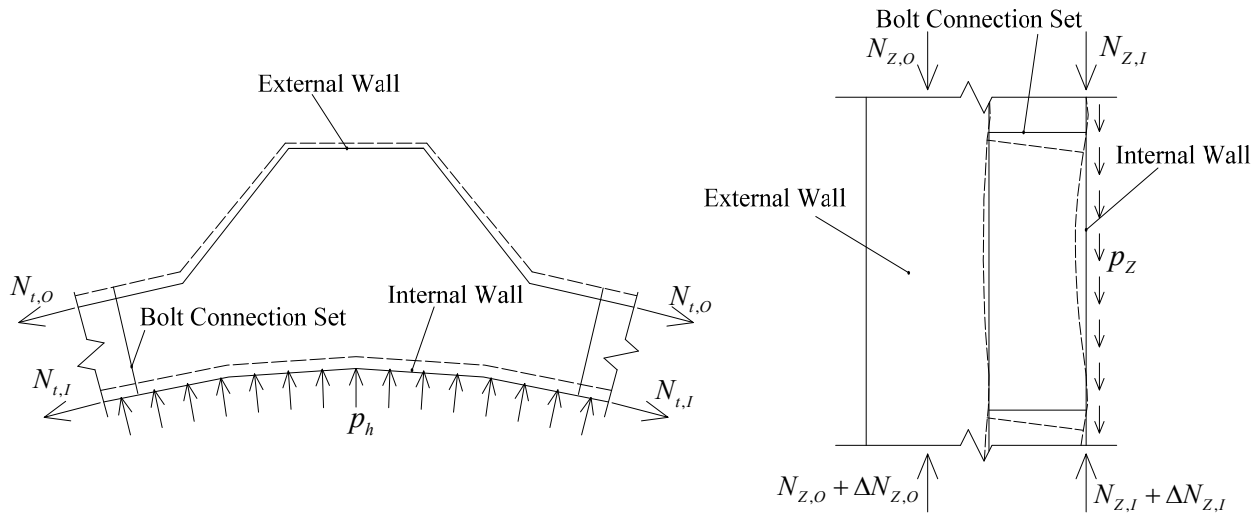
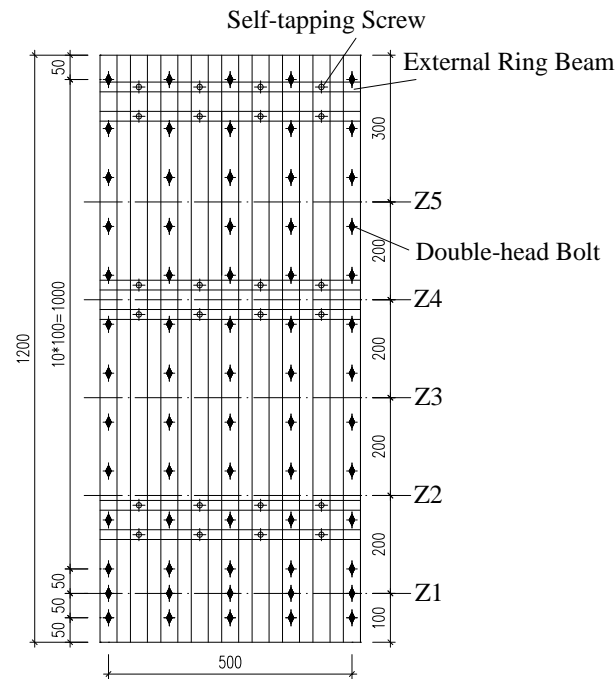


Figure 4. Force Diagram of the Silo under Grain Loads

4. STRUCTUREAL BEHAVIOR ANALYSIS

4.1 Research Object

The research object is an experimental silo model. Its internal diameter is 500mm, height 1200mm, and the spacing between the internal and external walls 25mm. For more details of the experimental silo model design, experiment process and results analysis, refer to Ref.[18]. In Figure 5, the external wall uses the YX 35-125-750 profiled steel plate, and the internal wall is a thin-walled circular plate of thickness 1mm. The 8-mm-diameter double-head bolts that connect the internal and external walls are placed with the vertical spacing of 100mm and are evenly spaced around a circle.



The washers not only distribute the loads of the nuts but also provide additional thickness for the internal wall at the very region. This experimental silo model chooses washers of the thickness 1.4mm, which increases the wall thickness at the region to 3.8mm.

(2) Boundary Conditions

The vertical and radial displacements of the internal wall, as well as the vertical displacement of the external wall are restrained at the bottom of the finite element model. This study uses shell elements to model the 14 steel angles, the bottoms of which are fixed.

(3) Loading Mode

According to Ref. [2], the silo is a deep bin if $h_n \geq 1.5 d_n$, a shallow bin if $h_n < 1.5 d_n$, where h_n is the computed height of the grains and d_n the inner diameter of the silo. Therefore, the experimental silo model in this study is a deep bin. At the depth S , the characteristic values of the horizontal pressure and vertical friction force on the unit area of the silo wall are calculated by the following formulas respectively [2]:

$$p_{hk} = \frac{\gamma \rho}{\mu} (1 - e^{-\mu k S / \rho}) \quad (1)$$

$$p_{fk} = \mu p_{hk} \quad (2)$$





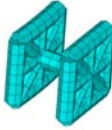

In the above formulas, γ is the gravity density of the grains, ρ the hydraulic radius $\rho = \frac{d_n}{4}$, μ the friction coefficient of the grains to the silo wall, and k the horizontal pressure coefficient of the grains.

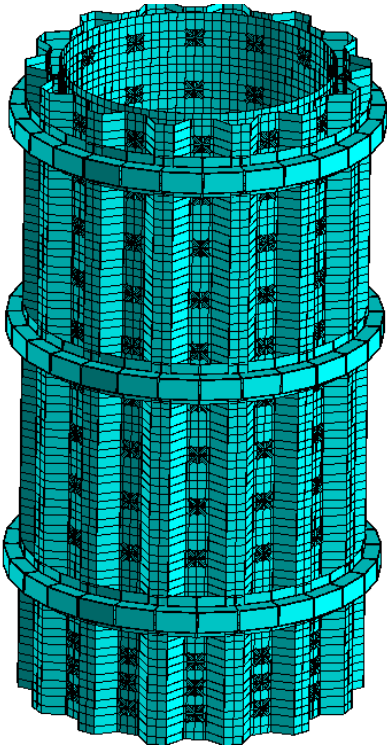
(4) Connection model between the internal and external walls

The cooperation between the internal and external walls to resist the loads is the most noteworthy feature of the silo, therefore, the selection of the connection model between the internal and external walls is crucial.

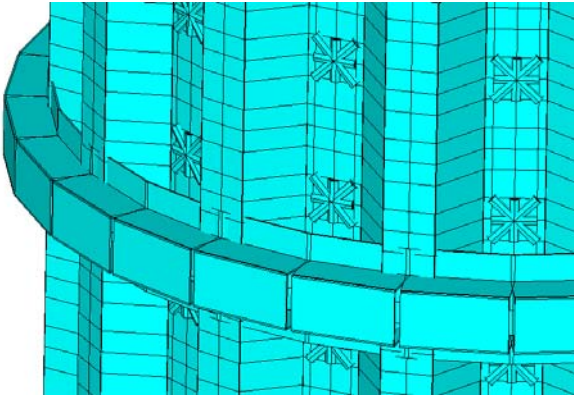
The double-head bolts are the only members transferring force between the internal and external walls. The loading process and transferring mechanism between the bolts and walls are relatively complex, which can be described by the contact nonlinearity in nature. If the contact elements are adopted, enormous work of modeling and computation will make it impractical to complete the design of the silo. To explore a simple and reliable connection model between the internal and external walls, six simulation plans (Table 1) are investigated after the actual bolt connection are carefully analyzed. In Table 1, A1 to A5 adopt the beam elements to simulate the bolts. In A1, either side of the bolt adopts only one node to connect the wall. A2 to A5 adopt different virtual beam elements to simulate the connection area between the washers and the walls. There is no need to model the bolts for A6 since it adopts the direct coupling approach.

Table 1. Six Connection Models between the Internal and External Walls

Model	A1	A2	A3	A4	A5	A6
Simulation shape	—	+	米	田	⊠	Coupling
Bolt illustration						



(a) Whole



(b) Local

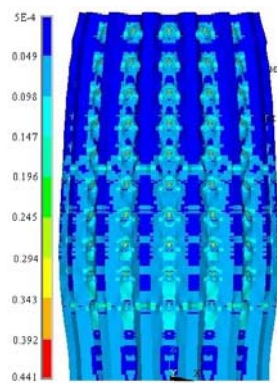
Figure 6. A3 Finite Element Model

4.2.2 Results Analysis

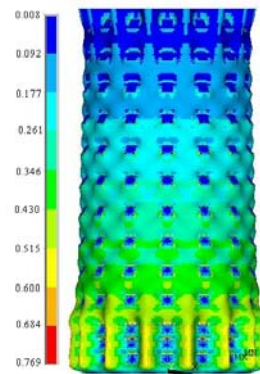
Linear elastic analyses of the six connection models are carried out. The typical Mises stress distributions of the silo walls are shown in Figure 7, and the maximum deformations are shown in Table 2.

From Table 2 and Figure 7 it is worth noting that:

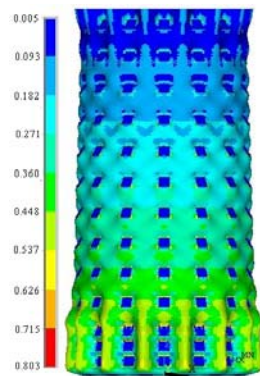
- 1) The stress and deformation of the silo walls are insignificant under the sand loads. The reason is that the silo wall thickness and the bolt diameter cannot be designed and processed with geometric similarity. Hence, a specifically designed loading plan should be adopted to increase the sand loads in the experiment. Although the absolute values of the stress and deformation are small, the relationship of the six models can still reflect some of the behavior rules of the silo.
- 2) The deformation characteristics of the six models are similar (the deformation of A3, A4 and A5 almost the same). The circumferential outward expansion of the walls is observed and the expansion near the external ring beams is relatively small. Local concave-convex deformation is also observed at the connection area between the washers and the walls and the support area.
- 3) Obvious stress concentration is seen at the support area and the connection area between the washers and the walls, however, the degree and distribution of stress concentration are quite different among the models. The most intense stress concentration of the external wall is found in A1 and the most intense stress concentration of the internal wall is found in A5. The stress distribution of the internal and external walls of A6 is the most uniform.
- 4) The circumferential deformations of the six models differ slightly yet the vertical deformations differ greatly. Of the internal walls, the maximum and minimum values of the maximum circumferential deformation are $8.87\text{E-}04\text{mm}$ (A1) and $7.71\text{E-}04\text{mm}$ (A6), the ratio of which is 1.15; of the external walls, the values are $4.57\text{E-}04\text{mm}$ (A2) and $3.74\text{E-}04\text{mm}$ (A6), the ratio 1.22. Of the internal walls, the ratio of the maximum value to the minimum value of the maximum vertical deformation is 1.68; of the external wall, the ratio is 1.56.



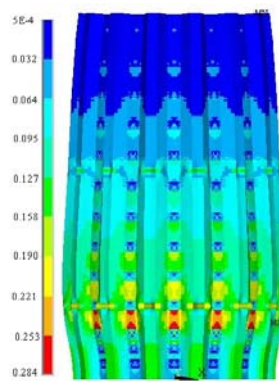
(a) A1's External wall



(b) A3's Internal wall



(c) A5's Internal wall



(d) A6's External wall

Figure 7 Typical Mises Stress Distribution of the Silo Walls (MPa)

Table 2. Maximum Deformation of the Silo Walls (mm)

Models	Internal wall		External wall	
	Circular	Vertical	Circular	Vertical
A1	8.87E-04	-8.11E-04	4.32E-04	-3.06E-04
A2	8.76E-04	-7.05E-04	4.57E-04	-3.69E-04
A3	8.67E-04	-6.77E-04	4.34E-04	-3.86E-04
A4	8.32E-04	-6.56E-04	4.06E-04	-3.71E-04
A5	8.34E-04	-6.47E-04	4.05E-04	-3.75E-04
A6	7.71E-04	-4.82E-04	3.74E-04	-4.76E-04

4.2.3 Bearing Patterns

Some results are obtained to further examine the bearing patterns of the internal and external walls of the six models, as shown in Table 3, Table 4 and Figure 8. In Table 3, the bearing efficiency of the horizontal pressure is defined as $\rho_t = N_{t,I} / (N_{t,I} + N_{t,O})$, where $N_{t,I}$ is the hoop force of the internal wall, $N_{t,O}$ the hoop force of the external wall in Figure 4. In Table 4, the bearing efficiency of the vertical friction force is defined as $\rho_z = N_{z,O} / (N_{z,I} + N_{z,O})$, where $N_{z,I}$ is the vertical force of the internal wall, $N_{z,O}$ the vertical force of the external wall in Figure 4. Due to the existence of supports at Z1, the results at Z1 are not taken into consideration.

Table 3. $N_{t,I}$, $N_{t,O}$ and ρ_t of Six Models

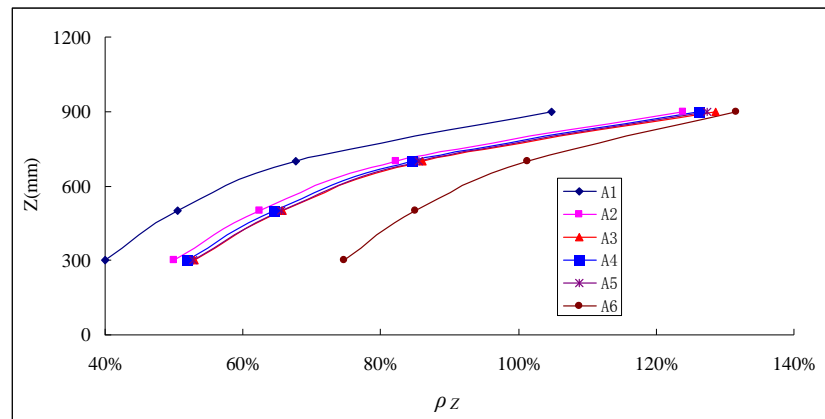
Position	A1			A2			A3		
	$N_{t,I}$	$N_{t,O}$	ρ_t	$N_{t,I}$	$N_{t,O}$	ρ_t	$N_{t,I}$	$N_{t,O}$	ρ_t
Z5	0.154	2.0E-04	99.9%	0.154	2.0E-04	99.9%	0.155	2.8E-04	99.8%
Z4	0.227	8.2E-04	99.6%	0.227	1.1E-03	99.5%	0.227	1.1E-03	99.5%
Z3	0.286	4.5E-04	99.8%	0.286	4.7E-04	99.8%	0.287	6.6E-04	99.8%
Z2	0.327	4.3E-04	99.9%	0.328	4.7E-04	99.9%	0.329	7.4E-04	99.8%
Position	A4			A5			A6		
	$N_{t,I}$	$N_{t,O}$	ρ_t	$N_{t,I}$	$N_{t,O}$	ρ_t	$N_{t,I}$	$N_{t,O}$	ρ_t
Z5	0.155	3.7E-04	99.8%	0.155	3.8E-04	99.8%	0.154	1.5E-04	99.9%
Z4	0.229	1.2E-03	99.5%	0.229	1.2E-03	99.5%	0.227	1.1E-03	99.5%
Z3	0.287	8.5E-04	99.7%	0.287	8.8E-04	99.7%	0.286	6.1E-04	99.8%
Z2	0.329	9.9E-04	99.7%	0.329	1.0E-03	99.7%	0.329	7.7E-04	99.8%

Note: $N_{t,I}$, $N_{t,O}$ in N/mm.

Table 4. $N_{Z,I}$, $N_{Z,O}$ and ρ_Z of Six Models

Position	A1			A2			A3		
	$N_{Z,I}$	$N_{Z,O}$	ρ_Z	$N_{Z,I}$	$N_{Z,O}$	ρ_Z	$N_{Z,I}$	$N_{Z,O}$	ρ_Z
Z5	2.8	-61.6	104.7%	14.0	-72.8	123.8%	16.8	-75.6	128.6%
Z4	-49.9	-104.3	67.7%	-27.4	-126.7	82.2%	-21.4	-132.8	86.1%
Z3	-139.4	-142.6	50.6%	-105.9	-176.1	62.5%	-96.5	-185.5	65.8%
Z2	-261.1	-173.7	40.0%	-217.2	-217.7	50.1%	-204.5	-230.3	53.0%
Position	A4			A5			A6		
	$N_{Z,I}$	$N_{Z,O}$	ρ_Z	$N_{Z,I}$	$N_{Z,O}$	ρ_Z	$N_{Z,I}$	$N_{Z,O}$	ρ_Z
Z5	15.4	-74.2	126.2%	16.1	-74.9	127.4%	18.6	-77.4	131.5%
Z4	-23.9	-130.3	84.5%	-22.2	-132.0	85.6%	2.1	-156.3	101.4%
Z3	-99.9	-182.1	64.6%	-97.3	-184.7	65.5%	-42.1	-239.9	85.1%
Z2	-208.9	-226.0	52.0%	-205.2	-229.6	52.8%	-110.5	-324.4	74.6%

Note: $N_{Z,I}$, $N_{Z,O}$ in N.

Figure 8. ρ_Z -Z Curves of Six Models

Note: Z is the height from the silo bottom

Results in Table 3, Table 4 and Figure 8 indicate the following conclusions:

1) The bearing patterns of the horizontal pressure of the six models are the same. The horizontal pressure is mainly resisted by the internal wall under tension, while the external wall does not resist much of the pressure. Among all the ρ_i 's of all the six models, the minimum is 99.5 % and the maximum is 99.9%. In addition, the hoop force of the external wall $N_{t,O}$ is slightly greater at Z4, as affected by the external ring beam.

2) The bearing patterns of the vertical friction force of the six models are the same, where the vertical friction force is carried by the external wall and the internal wall together, however, the efficiency varies at different height. The bearing efficiency of the vertical friction force increases along the upward direction of the silo. It even exceeds 100% at the upper part of the silo, where the internal wall is under vertical tension. In this situation, the external wall carries all the vertical friction force while balancing the vertical tensile force of the internal wall.

3) The performances of carrying the vertical friction force of the six models vary markedly. A1 delivers the worst performance, due to that it does not take into full consideration the stiffness of the connection area, thus resulting in a weak cooperation between the internal and external walls. A6 delivers the best performance due to that it ensures the deformation consistency of the coupled nodes of the internal and external walls, thus resulting in a great cooperation. The performances of A2 to A5 are in between.

The selection of connection model between the internal and external walls has a significant impact on the structural performance of the silo. To make the optimal selection, further verification and experimental studies are needed. For more details, refer to Ref. [18].

5. CONCLUSION

In this paper, a double-wall steel insulation silo with multiple bolted joints for grain storage is proposed, which is designed to improve the insulation effect and mechanical behavior of the traditional silo structure. Based on the study of its structural behavior, the following conclusions can be drawn:

- 1) The silo employs the planar thin-walled steel plate as the internal wall, and the continuous ladder-shaped profiled plate as the external wall. The cavity between the internal and external walls is filled with insulation material. The silo utilizes specifically designed bolt connections to connect the internal and external walls. The silo is environmentally friendly, featured with simple structure and high integrity. The design of the silo enables it to save energy and steel consumption with a pleasant appearance. The external and internal walls can together resist the wind, snow, earthquake and grain loads and the ring beams can promote the mechanical behavior and stability of the silo.
- 2) The horizontal pressure from the grains is mainly resisted by the internal wall under tension and the vertical friction force is carried by both the external and internal walls. The external wall helps carry the vertical friction force and provides effective supports to the stability of the internal wall.
- 3) The stiffness of the connection area must be appropriately simulated and the selection of connection model between the internal and external walls has a significant impact on the structural performance of the silo. To make the optimal selection, further verification and experimental studies are needed.

ACKNOWLEDGEMENTS

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