Research Article

Experimental Study on Mechanical Properties of Integrated Wall Panels of Grain Warehouse with “Thermal Insulation”

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The walls of grain cottage silos are still being built by clay brick masonry featured with single-structure form, poor air tightness, large workload of manual masonry on site, and huge consumption of raw materials and burning materials, which is not conducive to energy saving and environmental protection. In order to study the mechanical function of the new wall under the action of grain side pressure, the static loading test was conducted on the model of scaled-down wall panel under the action of side pressure. The damage process, the damage pattern, and the bearing capacity of the wall panel were studied through the analysis of the crack development process and distribution law to reveal the force characteristics of the wall panel. The test results show that the span deflection of the “structure-insulation” integrated wall panel under the lateral pressure meets the requirement of the limit state of normal use; the inner and outer leaf wall panels can work together under the action of the joint; the ratio of the load borne by the inner and outer leaf wall panels is equal to the ratio of their stiffness; the flexural stiffness of the wall panels after cracking is proposed based on the combined effect analysis. Based on the analysis of the combined effect, the degradation factor of the wall panel after cracking is proposed, and the deflection calculation formula of the inner and outer leaf wall panel is established, which provides a theoretical basis for the design and the promotion of the “structure-insulation” integrated wall panel.

1. Introduction

China is a large grain storage and transportation country, and cottage silo is the dominant silo type for grain reserves in China, accounting for more than 85% of the total silo capacity [1]. However, for a long time, cottage silo walls are still built with a large number of clay bricks masonry. Sintered bricks have the advantages of easy localization and good thermal performance, but the construction process is difficult, the maintenance cost is high, the manual masonry workload at the construction site is large, and the construction efficiency is low [2]. Due to the masonry process and other reasons, it is not easy to form full-mortar joints between clay bricks. The gaps between brick walls and seam beams and the natural shrinkage of mortar and concrete make it easy for through joints to appear, inevitably causing cracking phenomena; in the natural environment and the long-term role of microorganisms, chalking and cracks may show up on the wall, reducing the thermal insulation and airtight performance of the wall [3]. In addition, the mass production of sintered clay bricks occupies agricultural land, causing the destruction of available arable land and waste of resources, and many countries have made the call to ban the use of sintered clay bricks [4] and promote the widespread use of new wall materials [5]. At present, comprehensive innovations in the structural form of barn walls are being promoted in many countries. They are whole efforts to seek a new shed barn wall to replace the traditional sintered clay brick wall [6] so as to realize the sustainable development concept of “energy saving, land saving, and green and environmental protection” [7].

The “structure-insulation” integrated wall panel is proposed as a new type of wall panel, which consists of inner and outer leaf reinforced concrete wall panels, insulation panels, and connectors, and the insulation panels are placed between the inner and outer leaf concrete wall panels; the
three are organically connected through the connectors. In the process of grain storage, the lateral pressure of grain acts directly on the inner leaf wall, and the inner and outer leaf wall panels are jointly deformed by the connectors.

Compared with the external insulation and internal insulation wall, the built-in insulation board avoids the erosion of the natural environment and the impact of the grain loading process, realizing the same life of the insulation and structure, and the certain thickness of the insulation board ensures the thermal insulation performance of the wall board [8]. In recent years, the structure of the insulation board on the outside of the wall is prone to secondary disasters, such as fire and overall shedding [9]. The fire resistance of this wall is clearly inadequate compared with the wall we developed [10]. The study of new wall panel forms used in cottage barn buildings can overcome the shortcomings of clay brick walls, with good airtight performance, good insulation performance, energy saving, and environmental protection, to achieve the same life of building insulation and structure [11]. Common composite walls are usually used as vertical stressed members, mainly subjected to vertical pressure [12]. For example, brick Sandwich walls rely mainly on blocks to support the vertical forces transmitted from columns and roofs [13]; double-layered energy-efficient wall panels rely on GFRP to link in the middle, mainly to reduce the thermal conductivity between walls [14], and static tests of prestressed hollow-core panel walls show the need for additional prestressing to resist the vertical forces in the walls [15].

The “structure-insulation” integrated wall panels are subjected to the out-of-plane pressure of grain accumulation, which is less common, and the damage patterns and laws are not clear. In this article, the experimental study on the force performance of “structure-insulation” integrated wall panel under the action of grain lateral pressure is carried out to analyze the crack development process and distribution law, study the damage process, the damage pattern, and the bearing capacity of the wall panel, and reveal the force characteristics of the wall panel; the flexural stiffness degradation coefficient of the wall panel after cracking is proposed based on the combined effect analysis, and the flexural stiffness degradation coefficient of the wall panel after cracking is established. The deflection calculation formulae of inner and outer leaf wall panels are proposed based on the combined effect analysis, and the reference is provided for their design and engineering application in grain cottage silos.

2. Experimental Situation

2.1. Model Design. A 1/3 scale model is used in this test. The wall board is composed of inner and outer reinforced concrete wall board, insulation board, and connectors [16]. The insulation board is placed between inner and outer concrete wall boards. The insulation board is placed between inner and outer concrete wall boards, and they are organically connected by GFRP connectors [17]. The wall board structure diagram is shown in Figure 1. The size of the specimen is 2400 mm × 2400 mm, the thickness of the inner leaf wall is 100 mm, the thickness of the extruded polystyrene insulation board is 30 mm, and the thickness of the outer leaf wall is 40 mm. HRB400-type steel bar is used in the steel mesh in the inner and outer leaf wall boards, the double-layered bidirectional arrangement steel bar in the inner leaf wall, and the single-layered bidirectional arrangement steel bar in the outer leaf wall [18]. The GFRP (glass fiber reinforced plastic) connectors are arranged in a rectangular and uniform manner in the wall board, with a spacing of 500 mm × 500 mm, and a spacing of 200 mm × 200 mm at the edge of the wall board.

2.2. Material Tests. The concrete strength grade is C30, and the specimens are made by simultaneously making 3 concrete cube specimens with dimensions of 150 mm × 150 mm × 150 mm, and the specimens are cured under the same conditions for 28 days for concrete compressive strength test, and the compressive strength level is 30.1 MPa [19], the elastic model is 2.98 × 104 MPa, and the reinforcing steel mesh in the inner and outer leaf wall slabs is HRB400-type reinforcement; 3 pieces of each specification were intercepted on the parent material for reinforcement tensile test. GFRP material was used for the connectors, and the tensile performance test results of the connectors are shown in Table 1. The insulation board is made of extruded polystyrene foam, and three 100 mm × 100 mm × 50 mm insulation boards are intercepted on the base material for compression performance test; the test results are shown in Table 2.

2.3. Loading Scheme. Under the actual grain load condition, the wall board was subjected to lateral pressure with triangular variation trend outside the plane. This type of load is difficult to achieve in the laboratory. Triangular load is not easy to control. This test adopts a reaction device composed of four 8-m-high reaction frames and an 8-m-long reaction beam to support the specimen horizontally. The Actuator applies an out-of-plane concentrated load and is transferred to the steel plate by two-stage distribution beam. Then, 30-mm-thick coarse sand is tiled between steel plate and specimen and surface load is transferred to specimen, as shown in Figure 2.

To ensure the normal operation of the loading device and instrument, the specimen is preloaded in three stages after installation. When loading formally, the load control method is adopted. The initial load value is 14.32 kN of the upper loading device, and the load value applied at each stage is 10 kN. When the loading is close to the cracking load, the loading value at each stage is 5 kN; after the specimen is cracked, the loading value for each level is 10 kN. After each level is loaded, the data are collected after the data remains stable, and the crack width is drawn and measured until the specimen is broken.

2.4. Measuring Point Layout. The main test contents of this test are as follows: deflection, strain (tensile reinforcement, concrete, connectors), and cracking mode of wall panel. The concrete contents are as follows:
In the test, 10 displacement meters with a measuring range of 50 mm were used to measure the deflection of the wallboard, 9 displacement measuring points (W − 1~W − 9) are arranged at the bottom of the outer wall panel and a displacement measuring point (W N-1) is arranged at the bottom of the inner wall plate. Because the deflection of the middle part of the inner wall cannot be measured directly, a steel pipe with an inner diameter of 8 mm and a wall thickness of 0.5 mm is embedded in the midspan of the outer leaf wallboard and the insulation board when the test piece is poured. Contact the thimble of the displacement meter through the steel pipe with the inner wall panel to measure the deflection of the middle part of the inner leaf wall plate span. Displacement measurements point layout is shown in Figure 3(a).

The main test contents of strain are tensile reinforcement strain, concrete strain, and joint strain. The strain measuring point of tensile steel bar is expressed as S (S-1, S-2 the strain of tensile steel bar in x and y direction is expressed, respectively). Before the specimen is poured, a two-way BGK-4200 vibrating string strain gauge is embedded in the middle part of the inner and outer wall panels. To measure the tensile and compressible strain of inner and outer wall panel concrete, connector strain is expressed in L, and the strain measuring point layout is shown in Figure 3(b), respectively.

(1) The method of combining crack width reading instrument and magnifying glass observation is used to describe the occurrence and development of cracks and to record the crack width and the corresponding load value.

3. Test Results and Analysis

3.1. Test Results. During the loading process, the steel bars being pulled off did not occur in this experiment. The concrete was crushed, and the deflection was too large, so the test used the crack width to judge whether the wall plate reached the bearing capacity limit state; when the crack width was greater than 1.5 mm, the specimen was regarded as reaching the bearing capacity limit state, and the test ends when this level is reached. The crack distribution of the wall panel is shown in Figure 4, and the specific damage process is as follows.

The inner leaf wall cracks first, and the sudden drop of stiffness after cracking leads to the redistribution of internal force; the outer leaf wall also cracks immediately and continues to load; the inner leaf wall span middle part of the tensile reinforcement yields first, the outer leaf wall span middle part of the tensile reinforcement yields or does not yield, and the wall plate finally reaches the limit state of bearing capacity due to the excessive width of the crack. During the whole loading process, the deflection of the inner and outer leaf wall slabs always differed little, and they could be deformed together with good integrity under the action of...
the joint. The concrete strain of the outer leaf wall is smaller than the concrete strain of the inner leaf wall, and the inner leaf wall is the main flexural member, which is mainly subjected to lateral pressure. The GFRP connectors located in the middle part of the span are always under pressure, and the connectors at the corners are always under tension; the corner connectors resist the lateral pressure the most, and the maximum tensile strain of the connectors does not exceed 700 during the whole loading process; the strain level is low, and no damage occurs, which can better guarantee the integrity of the inner and outer leaf wall slabs.

3.2. Deformation Analysis. In order to analyze the deformation performance of the inner and outer leaf wall panels under the action of lateral pressure and the synergistic work of the two, nine displacement measurement points were arranged along the x and y directions at the bottom of the outer leaf wall panel, and one displacement measurement point was arranged at the bottom span of the inner leaf wall panel; the load-deflection relationship curve of each measurement point is shown in Figure 5.

It can be seen from the Figure 5 that the wallboard has the largest deflection in the middle of the span, followed by the 1/4 span, and the least deflection near the support. The deflection growth trends at measuring points W-2 and W-3 are similar to those at W-4 and W-5, indicating that the deformation of the wallboard is symmetric in the x and y directions. During the whole loading process, the slope of the load-deflection curve of the support is small, basically a straight line; the deflection growth rate of the span and 1/4 span increases obviously after the concrete cracking, and the slope of the load-deflection curve decreases obviously.

It can be seen from Figure 6 that the deflection curves in x and y directions are flat before each specimen reaches the cracking load, and the difference between the deflection
values in the midspan part and the 1/4-span part is not significant. With the increase in load and the appearance of cracks, the change of deflection is gradually accelerated, and the development rate of deflection in the middle part of the span is obviously higher than that in the 1/4 span part, and it can be seen from Figure 4 that the shape of deformation of the wall plate is "butterfly."

Comparing the deflection changes in the span part of the inner and outer leaf wall panels, it can be seen from Figure 7 that the deflection curves of the two almost overlap during the whole loading process, indicating that the GFRP connectors can effectively link the inner and outer leaf wall panels together in the wall panel, so that the two can deform synergistically and share the force, making the wall panel have good integrity under the action of lateral pressure.

3.3. Strain Analysis

3.3.1. Concrete Strain. The variation of concrete strain values along the height of the cross-section in the span section is shown in Figure 8, where the horizontal coordinates are the strains at the measured points before, during, and after the cracking of the concrete, and the vertical coordinates are the depth of the section. From the figure, it can be seen that the upper and lower surfaces of the inner and outer leaf wall panels exhibit compression and tension behaviors, and there exist respective neutral axes within the section height and deformation around the respective neutral axes, which are in accordance with the assumption of flat section, respectively. Under the action of lateral pressure, the inner and outer leaf wall panels are each subjected to a portion of the load, and the magnitude of the load borne is proportional to their respective stiffnesses, and the wall panels exhibit a certain degree of noncombination according to the basis for the classification of fully combined, partially combined, and noncombined walls. The analysis of deflection and crack development of the specimen shows that the wall panel can meet the requirements of the limit state of normal use when the grain loading height is 7.2 m. In the design calculation of the “structure-insulation” integrated wall panel of the cottage barn, the design is carried out according to the noncombined wall panel, considering only the inner leaf wall as the structural bearing member, which bears the lateral pressure of the grain, and the outer leaf wall as the protective insulation. Only the inner leaf wall is considered as the structural bearing element, which is responsible for the lateral pressure of grain, and the outer leaf wall is responsible for the protection of insulation board.

3.3.2. Steel Strain. According to the collected data of reinforcement strain, the measurement points in the x and y directions of the span part of the inner leaf wall were selected, and the load-strain relationship curve of the tensile reinforcement was drawn, as shown in Figure 9.

From the figure, it can be seen that at the early stage of loading, the strain increment of the reinforcement is small and the strain curve is basically linear in development. When the loading reached the first crack in the midspan area, the load-strain curve showed an inflection point and the slope of the curve slightly decreased. Continuing to load, with the development and extension of cracks at the bottom of the slab, the concrete in the tensile zone gradually withdraws from the work, and the increment of the strain of the reinforcement under each level of loading is greater than that at the uncracked stage, and the slope of the curve gradually decreases. When the specimen reached the ultimate state of load carrying capacity, the strain of the tensile reinforcement in the span part was 2368 με and 2511 με in the x and y directions, respectively, and yielding occurred.

3.3.3. Connector Strain. In order to analyze the stress of the connectors in different parts of the wall board under the action of lateral pressure, the load-strain relationship curve is drawn by selecting the strain measuring points of the connectors in the middle and corner of the span and along the diagonal direction of 45°, as shown in Figure 10.
From the diagram, it can be seen that the connectors in the middle part of the span are always under pressure, the connectors in the corner are always pulled, and the connectors along the diagonal direction of 45° are under pressure at the initial stage of loading and gradually become pulled with the increase of the load. At the beginning of loading, the strain of the connectors increases linearly, and with the increase of load, the strain development accelerates gradually. The strain of the connector at the corner is greater than the strain of the connector in the midspan and diagonal directions, and the corner connector has the greatest resistance to lateral pressure.

During the whole loading process, the maximum tensile strain is not more than 700 με, the strain level is low, and there is no connection failure.

4. Model Calculation Methodology

4.1. Computational Modeling. The calculation of stiffness and deflection of “structure-insulation” integrated wall panels for cottage barn can be divided into two stages: uncracked concrete stage and cracked concrete working stage. The calculation of the uncracked concrete phase of the composite wall slab is usually based on the calculation
of the concrete two-way slab, but the new structural system is divided into inner and outer leaf walls, and the stiffness of the two leaf walls are brought into the formula as follows:

\[
f = \partial_f \times \frac{P l^4}{B} = \partial_f \times \frac{P l^4}{B_{\text{inner}} + B_{\text{outer}}}
\]

\[
= \partial_f \times \frac{B_{\text{inner}} P}{B_{\text{inner}} + B_{\text{outer}}} \times \frac{l^4}{B_{\text{inner}}}
\]

\[
= \partial_f \times \frac{B_{\text{outer}} P}{B_{\text{inner}} + B_{\text{outer}}} \times \frac{l^4}{B_{\text{outer}}}
\]

Thus,

\[
P_{\text{inner}} = \frac{B_{\text{inner}} P}{B_{\text{inner}} + B_{\text{outer}}}
\]

\[
P_{\text{outer}} = \frac{B_{\text{outer}} P}{B_{\text{inner}} + B_{\text{outer}}}
\]

\[
\frac{P_{\text{inner}}}{P_{\text{outer}}} = \frac{B_{\text{inner}}}{B_{\text{outer}}}
\]

where \( f \) is the deflection of the integrated wallboard, \( \partial_f \) is the calculation coefficient of deflection of two-way plate. \( P \) is the load per unit area. \( L \) is the short span of the integrated wall panel; \( B \) is the bending stiffness of integrated wall panels.
It can be seen from formula (3) that under the action of lateral pressure, the inner and outer leaf walls each bear a part of the load, and the ratio of the load borne is equal to the ratio of their stiffnesses. The flexural stiffness $B$ of the wall slab is a constant quantity when there is no crack in the concrete because concrete is an elastic-plastic material worked with cracks in the service phase, and the appearance of cracks makes the development of deflection accelerate, the flexural stiffness of the wall slab gradually decreases, and the stiffness $B$ gradually becomes a changing quantity, in line with the “structure-insulation” integrated wall slab deflection of cottage barn” integrated wall panel deflection change process.

Therefore, the spanwise stiffness and deflection of inner and outer leaf wall panels in the elastic stage are calculated as shown in (4) and (5).

$$B_{\text{inner}} = \frac{E_c h_{\text{inner}}^3}{12(1-v_c^2)}.$$  \hfill (4)

$$B_{\text{outer}} = \frac{E_c h_{\text{outer}}^3}{12(1-v_c^2)}.$$  \hfill (5)

where $B_{\text{inner}}, B_{\text{outer}}$ are initial bending stiffness of inner and outer wall panels; $E_c$ is the modulus of elasticity of concrete; $h_{\text{inner}}, h_{\text{outer}}$ are the thickness of inner and outer wall panels;
$V_C$ is the Poisson’s ratio of concrete; $\vartheta_j$ is the calculation coefficient of deflection; $P_{inner}, P_{outer}$ are the load bearing on inner and outer wall panels per unit area; $l$ is the span of the integrated wallboard, whichever is the minimum of $l_x$ and $l_y$.

However, the concrete strain has been concluded that the “structure-insulation” integrated wall slab exhibits non-combination, and after entering the elastoplastic phase, with the increase of load, cracks appear and extend, the concrete in the tensile zone gradually withdraws from the work, and the initial flexural stiffness $B$ of the wall slab decreases continuously, which gradually increases the error between the test deflection value and the theoretical formula calculation value, and the above theory is not in adaptation to this calculation.

In this article, the initial flexural stiffness $B$ of the wall slab is assumed constant before and after the concrete cracks. Based on the test measured deflection values of the inner and outer leaf wall slabs under all levels of loading, the Taguchi analysis method [20] is used to derive the stiffness degradation coefficients of the inner and outer leaf wall slabs, which are multiplied by the stiffness degradation coefficient on the basis of the initial flexural stiffness $B$, so that the stiffness calculation formula after cracking is modified to obtain the cross-sectional flexural stiffness of the inner and outer leaf wall panels in the elastic-plastic phase of the wall panel, as shown in formula (5).

When $P > P_{cr}$,

$$B = \vartheta_{inner} B_{inner} + \vartheta_{outer} B_{outer},$$

(6)

where $B_{inner}$ is the initial bending stiffness of inner wall section; $B_{outer}$ is the initial bending stiffness of outer wall section; $\vartheta_{inner}$ is the coefficient of stiffness degradation of inner wall; $\vartheta_{outer}$ is the coefficient of stiffness degradation of outer wall; $P$ is the wallboard load.

4.2. Calculation Model Validation. The deflection of the span part of the wall slab is still calculated according to formulas (5) and (6), and the deflection values of the inner and outer leaf wall slabs under all levels of loading after the concrete cracking can be obtained, as shown in Figure 11. It can be seen from the figure that the error between the calculated value and the test value in the elastic phase is small, and the error between the two gradually increases after entering the elastic-plastic phase, although the calculated deflection value of the method in this article is basically within 7% of the error between the wall slab after cracking and the test deflection value, which is more consistent.

5. Conclusion

In this article, “structure-insulation” integrated wall panel serving as a new type of structural system of cottage barn is proposed, which has excellent thermal insulation performance, good airtightness, energy saving, and environmental protection and realizes the same life of building insulation and structure. It makes up for the defects of sintered clay brick wall as a more ideal structural form and has a wide application future in cottage barn building.

The static loading test of the “structure-insulation” integrated wall panel of cottage barn under the action of lateral pressure reveals that the whole process of damage manifests itself: the inner leaf wall cracks first, the sudden drop of stiffness after cracking leads to the redistribution of internal force, and the outer leaf wall also cracks immediately. As the loading continues, the tensile reinforcement in the span of the inner leaf wall yields first, and the tensile reinforcement in the span of the outer leaf wall yields afterwards.

According to the combined effect analysis, the flexural stiffness and deflection calculation methods of the inner and outer leaf walls are established in the elastic phase, and the
flexural stiffness degradation coefficients of the walls after cracking are proposed in the elastoplastic phase to optimize the deflection calculation formulae of the inner and outer leaf walls after cracking. The research of this article provides designers with accurate calculation methods for the design of "structure-insulation" integrated wall panels and establishes experimental verification for the promotion of this new type of wall. Subsequently, we continue our research for the construction, assembly, and other aspects of the wall in the actual construction to facilitate the promotion and use.

Data Availability

In this present study, an integrated wall panels of grain warehouse with "thermal insulation" is introduced, and the GFRP connectors added in the integrated wall panels are designed. The bending stiffness degradation coefficient and the deflection calculation formula of the integrated wall panels are established through experiment and theoretical methods. The data of the article are available from the corresponding author upon request via e-mail.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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