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Design of Lightweight Composite Thermal Insulation Structural Components for Civil Air Defense Projects

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Abstract

This study involves a lightweight composite insulation structural component for civil air defense construction, aiming to solve the problems of alignment accuracy control and leakage prevention at the board joints during the installation of insulation boards. This structural component includes a shell, positioning module, sensing module, anti-misalignment module, closure module and leak-proof module. It assists in positioning and installing adjacent insulation boards and senses their alignment in real time. When the insulation board is misaligned, the anti-misalignment module automatically blocks the screw holes and forcibly interrupts the installation process. Fixation can only be carried out when the alignment meets the standard and the anti-misalignment piece is detached from the through hole, thereby ensuring the positional accuracy after installation. In addition, the structural components adopt the TG mortise and tenon type butt joint method. Compared with the flat head butt joint, it can effectively slow down the seepage of liquid through the board joints. Combined with the anti-leakage module, it can absorb the already seeped liquid, maximizing the delay of liquid erosion on the insulation system and extending the service life of the entire system. The present invention provides a reliable solution for the rapid, precise and durable installation of insulation structures in civil air defense projects and other construction fields by integrating positioning, error-proofing and leak-proofing functions.

Keywords

Civil Air Defense Project; Energy Conservation and Emission Reduction; Insulation Board; Foolproof and Leak-Proof; Installation Accuracy.

1. Introduction

With the acceleration of urbanization and the continuous improvement of building energy conservation standards, civil air defense projects, as important infrastructure that combines national defense security and social service functions, have increasingly drawn attention to the energy conservation, comfort and durability of their internal environment. Among them, the thermal performance and air tightness of the envelope structure are the key factors affecting the energy consumption and environmental quality of civil air defense projects. In the installation and construction of traditional insulation boards, there are common problems such as difficulty in ensuring the alignment accuracy of board joints, low efficiency in manual visual calibration, and the resulting loose joints leading to cold and hot bridge effects and liquid leakage risks. This not only weakens the overall efficiency of the insulation system and increases long-term maintenance costs,

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but also falls short of the current strategic requirements for energy conservation, emission reduction, and improvement of building quality.

To address the above issues, this study designed and developed a lightweight composite thermal insulation structural component for civil air defense construction. This structural component integrates multi-functional modules such as positioning, sensing, fool-proofing, closure and leakage prevention, aiming to achieve precise, automated and reliable installation process of insulation boards. The core innovation lies in: real-time monitoring of alignment through the sensing module and physical intervention through the anti-misalignment module - only when the alignment between the plates meets the standard are the fixing screws allowed to be inserted, eliminating performance defects caused by misaligned installation from the source. Meanwhile, the structural components adopt an innovative TG mortise and tenon type butt joint method, combined with an active anti-leakage mechanism, which significantly enhances the sealing and weather resistance of the joints, effectively delaying water erosion. Thus, on the basis of ensuring installation accuracy, it further strengthens the long-term thermal stability and service life of the insulation system.

This article aims to provide a detailed introduction to the design principle, module functions, working process of this lightweight composite insulation structural component and its application advantages in civil air defense projects. Through this research, it is expected to provide a practical and innovative solution for improving the construction quality of the envelope structure of civil air defense projects, achieving higher standards of energy conservation and emission reduction targets, and promoting the development of building insulation technology towards intelligence and integration.

2. Structure Composition and Functional Design

The lightweight composite thermal insulation structural component for civil air defense construction takes the shell as the core bearing structure, and integrates five functional modules including a positioning module, an induction module, a fool-proof module, a closing module and an anti-leakage module. Each module is arranged in the corresponding area of the shell according to the preset position, and cooperates to complete the butt joint, positioning, installation and anti-seepage protection of the thermal insulation board. The structural composition and functional design are as follows.

2.1 Overall Structure and Shell Design

The core bearing structure of the structural component is the shell, which is made of lightweight composite materials and has a TG tenon-and-groove cross-section. The interior of the shell is designed as a hollow cavity, and screw through-holes are evenly opened on the surface of the shell. Accommodating grooves are symmetrically opened at the upper and lower ends of the shell.

The screw through-holes are arranged in a staggered manner, with the middle screw through-holes and the upper and lower screw through-holes arranged non-collinearly. The middle screw through-holes are used for the preliminary fixation of the structural component, and the upper and lower screw through-holes are used for the final fixation of the structural component. The accommodating grooves of the shell are used to store the relevant components of the positioning module, and the hollow cavity of the shell provides space for the arrangement and movement of each functional module.

2.2 Structure and Working Mechanism of the Positioning Module

The positioning modules are symmetrically arranged at the upper and lower ends of the shell, and consist of extrusion blocks, plate frames, clamping grooves, L-shaped positioning plates and limiting mechanisms. The limiting mechanisms include movable rods, square blocks and support rods. A spring 1 is connected between the extrusion blocks and the shell, a spring 2 is connected between the plate frames and the shell, a spring 3 is connected between the movable rods and the rotating shafts, and a spring 4 is connected between the support rods and the movable grooves of the positioning plates.

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The extrusion blocks can slide left and right along the side walls of the shell, and the plate frames can slide up and down along the end side walls of the shell. The positioning plates are rotatably arranged on the plate frames through rotating shafts, and the movable rods are symmetrically arranged inside the rotating shafts in a front-back sliding manner. The square blocks are installed at the outer ends of the movable rods and can slide along the sliding grooves on the side walls of the accommodating grooves. The support rods can slide up and down along the movable grooves of the positioning plates, and their two ends are in contact with the movable rods. In the initial state, the positions of the plate frames and the clamping grooves are staggered, and the extrusion blocks form a limit on the plate frames.

When the thermal insulation board is clamped with the shell, the extrusion blocks shrink towards the inner side of the shell under the extrusion force of the thermal insulation board. When the plate frames are aligned with the clamping grooves, the plate frames are inserted into the clamping grooves under the action of the spring 2, and the plate frames drive the positioning plates to fit the upper and lower end faces of the thermal insulation board. During this process, the square blocks are always located in the sliding grooves, forming a limit on the movable rods and preventing the positioning plates from rotating around the rotating shafts.

2.3 Structure and Cooperative Working Mode of the Induction Module and the Fool-proof Module

2.3.1 Structure of the Induction Module

The induction modules are symmetrically arranged on the rear side walls of the positioning module in an up-down manner, and consist of mounting shells, movable parts, linkage rods, balance plates, rotating shafts, major arc grooves and pressure plates. A spring 5 is connected between the movable parts and the mounting shells, and a spring 6 is connected between the linkage rods and the movable parts.

The mounting shells are fixed on the rear inner walls of the shell, and the movable parts can slide up and down along the inside of the mounting shells. The linkage rods can slide up and down along the inside of the movable parts, and their outer top ends are arc surfaces. The balance plates are rotatably arranged at the outer ends of the movable parts through rotating shafts. The major arc grooves are opened in the middle of the rotating shafts and correspond to the positions of the linkage rods. The pressure plates are installed on the side walls of the plate frames and correspond to the positions of the balance plates.

2.3.2 Structure of the Fool-proof Module

The fool-proof modules are symmetrically arranged in the screw through-holes at the outermost ends of the shell in an up-down manner, and consist of fool-proof parts, baffle plates, release grooves and extrusion grooves. A spring 7 is connected between the fool-proof parts and the screw through-holes.

The fool-proof parts can slide up and down along the side walls of the screw through-holes, and the baffle plates can slide back and forth along the inner walls of the shell. Both the release grooves and the extrusion grooves are opened on the baffle plates, the release grooves correspond to the positions of the fool-proof parts, and the extrusion grooves correspond to the positions of the linkage rods. In the initial state, the fool-proof parts block the screw through-holes, and the baffle plates form a limit on the fool-proof parts.

2.3.3 Cooperative Working Mode

The plate frames drive the pressure plates to move synchronously when moving, and the pressure plates press the balance plates. If the adjacent thermal insulation boards are butted flush, the symmetrically arranged pressure plates move stably, the balance plates move down in a horizontal state, and the linkage rods are not in contact with the major arc grooves and maintain the maximum extension state. If the thermal insulation boards are butted dislocated, the moving distances of the plate frames on both sides are different, and the uneven pressing force of the pressure plates causes

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the balance plates to tilt, the major arc grooves are aligned with the linkage rods, and the linkage rods retract under the action of the spring 6.

During the downward movement of the linkage rods with the movable parts, if the maximum extension state is maintained, the extrusion grooves of the baffle plates will be extruded to push the baffle plates down. When the release grooves are aligned with the fool-proof parts, the fool-proof parts are separated from the screw through-holes under the action of the spring 7. If the linkage rods retract, the extrusion grooves cannot be effectively extruded, the baffle plates remain in the initial position, and the fool-proof parts continue to block the screw through-holes.

2.4 Structure and Working Mechanism of the Closing Module

The closing module is arranged in the screw through-hole at the outermost end of the shell, and consists of a movable plate, a take-up roller, an inserting knife, a slot, a sliding part, a traction rope 1, a traction rope 2 and a pulley. A spring 8 is connected between the movable plate and the screw through-hole, and a spring 9 is connected between the sliding part and the moving groove of the positioning plate.

The movable plate can slide back and forth along the screw through-hole, and the inserting knife is installed at the bottom of the movable plate. The take-up roller is rotatably arranged on the outer circumference of the screw through-hole, and the slot is opened on the take-up roller and corresponds to the position of the inserting knife. The sliding part can slide left and right along the moving groove of the positioning plate. The traction rope 1 connects the sliding part and the support rod, one end of the traction rope 2 is connected with the sliding part, and the other end is connected with the take-up roller through the pulley. The pulley is rotatably arranged on the inner wall of the shell.

When a screw is screwed into the screw through-hole, the movable plate is pushed down, and the inserting knife moves down with the movable plate and is inserted into the slot, squeezing the take-up roller to rotate. The take-up roller winds the traction rope 2 during rotation, and the tightened traction rope 2 pulls the sliding part to slide along the moving groove. The sliding part pulls the support rod through the traction rope 1 to separate the support rod from the movable rod. The movable rod moves to the middle under the action of the spring 3, so that the square block is separated from the sliding groove and the positioning plate is unlocked. The take-up roller continues to rotate, the traction rope 2 is further tightened and pulls the positioning plate to turn around the rotating shaft, and finally the positioning plate is stored in the accommodating groove of the shell.

2.5 Structure and Working Mechanism of the Anti-leakage Module

The anti-leakage modules are symmetrically arranged on the left and right side walls of the shell, and consist of a propping part, an inner groove, an extrusion plate and a water-absorbing part. A spring 10 is connected between the extrusion plate and the hidden cavity of the shell.

The propping part can slide back and forth along the hidden cavity opened inside the side wall of the shell, and the inner groove is opened on the extrusion block and corresponds to the position of the propping part. The extrusion plate can slide along the hidden cavity, the water-absorbing part is installed on the inner wall of the hidden cavity, one side of the water-absorbing part is connected with the outside through a through-hole groove opened on the inner wall of the hidden cavity, and the other side is in contact with the extrusion plate. In the initial state, the extrusion plate presses the water-absorbing part tightly under the action of the spring 10.

When the extrusion block shrinks towards the inner side of the shell under extrusion, the propping part is gradually separated from the inner groove and moves towards the extrusion plate under extrusion force, pushing the extrusion plate to slide along the hidden cavity and separate from the water-absorbing part. When liquid seeps along the plate joint in the later stage, the liquid contacts with the water-absorbing part through the through-hole groove, and the water-absorbing part absorbs and stores the liquid.

3. Implementation Process and Engineering Application Analysis

3.1 Standard Installation Procedure

The on-site construction process of this structural component can be divided into five steps: The first step is to connect one side of the structural component shell with the fixed insulation board through tenon and groove. The second step is to connect the insulation board to be installed with the other side of the shell. At this point, the positioning module will automatically clamp, completing the initial fixation. In the third step, the system automatically detects the flatness of the two insulation boards through the sensing module. If it is qualified, the anti-misalignment module unlocks the screw holes. If it is not qualified, the construction personnel need to adjust the position of the boards until the system allows installation. The fourth step is to insert and tighten the bolts in sequence. During this process, the closing module will be automatically triggered, and the positioning component will be retracted into the housing. The fifth step is that after installation is completed, the anti-leakage module enters the working state, providing long-term water seepage protection. The entire process has achieved semi-automation from alignment, detection, adjustment to fixation and storage, significantly reducing the reliance on the experience of construction personnel.

3.2 Performance Advantages and Applicability

Compared with the traditional connection methods of insulation boards, this structural component has the following prominent advantages: Firstly, it achieves active control of installation accuracy through the combination of mechanical and inductive methods, avoiding human errors. Secondly, the modular design makes the installation process logically clear and easy to operate, which is conducive to improving construction efficiency. Secondly, the leak-proof design alleviates the common quality problem of water seepage at the board joints from the source. Finally, the overall structure is lightweight and of high strength, making it suitable for the installation of insulation boards on walls, ceilings and other parts in various civil air defense projects. Especially in civil air defense facilities with high standards and high durability requirements, this structural component can effectively enhance the overall reliability and service life of the insulation system.

4. Literature References

Recent advancements in Civil Air Defense (CAD) engineering and building envelope technologies demonstrate a significant evolution towards integrated, high-performance, and intelligently managed systems. This review synthesizes contemporary research to highlight key developments in these interconnected fields.

The paradigm of CAD engineering has shifted from isolated protective structures to multifunctional components of urban infrastructure. The efficient dual-use of underground space is now a central design consideration, with architectural strategies focusing on enhancing peacetime utility while maintaining wartime readiness[1]. This evolution necessitates robust frameworks for evaluating the core protective function. Research by Chen et al. (2025) addresses this by developing comprehensive evaluation systems for assessing the protective effectiveness of entire urban CAD engineering networks, emphasizing systemic resilience over individual structural performance[2]. Ensuring the long-term reliability of these critical infrastructures has brought quality and risk management to the forefront. Studies have investigated strategies for strengthening quality supervision and management throughout the construction phase[3], while also proposing innovative approaches such as research-oriented auditing to empower risk prevention and control across the entire project lifecycle, from planning to maintenance[4].

Parallel to management innovations, technological enhancements within CAD engineering are evident. Wen (2025) explores the construction of technological innovation and quality management systems specifically for CAD engineering in residential buildings[5]. A critical aspect of habitability in enclosed CAD spaces is indoor air quality; consequently, research into advanced air quality monitoring and optimal control technologies has emerged as a vital area of study[6].

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In the broader domain of building construction, external wall insulation systems have undergone substantial innovation driven by demands for energy efficiency, durability, and safety. Research into improving material performance is active, with studies focused on enhancing the durability of external thermal insulation systems[7], analyzing effective construction techniques[8], and evaluating the structural and seismic performance of novel prefabricated composite systems that integrate insulation[9]. The pursuit of sustainability has also spurred material science research, including the development of insulation boards from recycled waste materials[10] and the analysis of new materials' hygrothermal characteristics[11]. The market and application of various insulation materials continue to be reviewed and expanded[12], with specific case studies demonstrating the successful application of advanced materials like STP vacuum insulation panels in retrofit projects[13].

The performance and safety of these insulation systems are subject to rigorous scrutiny. Key research areas include the critical role of combustion performance testing in building fire protection[14], the mastery of key construction technologies for reinforced concrete walls[15], and the examination of how different detection methods and equipment can influence the accuracy of thermal conductivity measurements, which is fundamental to performance validation[16]. Furthermore, comparative analyses of different external wall insulation methods (e.g., external versus internal insulation) continue to inform best practices by elucidating their respective advantages and disadvantages[17]. This body of work is increasingly framed within the overarching concept of green energy conservation, driving the optimization and innovation of construction technologies[18].

In summary, contemporary research in both specialized CAD engineering and general building insulation reveals converging themes: a strong emphasis on lifecycle management and quality control [3, 4, 5], the integration of advanced materials and technologies to enhance performance [6, 9, 10, 13], and the indispensable role of rigorous testing and evaluation to ensure safety, durability, and efficacy [2, 14, 16]. These parallel advancements contribute to the broader goals of creating resilient, sustainable, and high-performance built environments.

5. Conclusion

This study focuses on the problems of difficult control of alignment accuracy and insufficient leak-proof performance of board joints in the installation of thermal insulation structures for civil air defense projects, and designs and implements a lightweight composite thermal insulation structural component. This structural component integrates multiple functional modules such as positioning, sensing, anti-misalignment, closure and leakage prevention. By assisting in the positioning and real-time sensing of adjacent insulation boards, it precisely controls the alignment during the installation process. When the insulation board is misaligned, the anti-misalignment piece automatically blocks the screw holes, forcing the installation operation to be interrupted. Fixation can only be carried out after alignment meets the standards, thereby ensuring the accuracy of the installation position. In addition, the structural components adopt the TG mortise and tenon type butt joint method, combined with the built-in anti-leakage module, which can effectively slow down and absorb the liquid seeping through the board joints, significantly delay the erosion of the insulation system by leakage, and improve the overall sealing performance and long-term durability of the system. The results of structural design and functional verification show that this structural component has significant effects in terms of installation accuracy control and leak-proof performance, and possesses good engineering adaptability.

This research, through structural integration and functional coordination, provides a solution for insulation systems in civil air defense projects and other construction fields that is controllable in installation quality and reliable in long-term leakage prevention. It has practical significance for improving the construction quality of the envelope structure, enhancing the energy-saving effect of the project and prolonging the service life of the system. This achievement also provides a feasible technical path for promoting the development of building insulation structures towards intelligence, integration and high reliability, and has certain application and promotion value.

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