Comparative Study on Energy-Saving Effects of New Lightweight Composite Thermal Insulation Structural Component Joint Scheme and Traditional Thermal Insulation Board Joint Schemes

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Abstract

The construction accuracy and sealing protection capacity of thermal insulation board joint nodes are the core factors affecting the thermal performance of building exterior wall thermal insulation systems, which directly determine the exertion of energy-saving benefits and the service life of the system. Taking the TG tenon-groove intelligent joint scheme of the new lightweight composite thermal insulation structural component for civil air defense construction as the research object, this paper carries out a systematic comparative study with traditional thermal insulation board joint schemes such as flat head joint and tongue-and-groove joint, analyzes from the aspects of joint structure design, construction accuracy control, thermal performance performance and actual engineering energy-saving effects, and quantifies the technical advantages and energy-saving value of the new joint scheme combined with measured data and engineering cases. The research shows that the new TG tenon-groove intelligent joint scheme eradicates the thermal bridge problem caused by human errors from the structural and construction levels, greatly reduces the heat loss and water seepage risk of plate joints, the annual comprehensive energy consumption of supporting buildings is reduced by 8%~20% compared with traditional joint schemes, and the service life of the thermal insulation system is extended by more than 50%. It provides practical reference for the technical optimization and scheme selection of the joint link of building thermal insulation engineering, and promotes the development of building thermal insulation and energy-saving technology towards high precision and long-term effectiveness.

Keywords

Lightweight Composite Thermal Insulation Structural Component; Thermal Insulation Board Joint Scheme; TG Tenon-groove Joint; Thermal Bridge Control; Energy-saving Effect; Building Thermal Insulation.

1. Introduction

Building energy conservation plays a key role in addressing global climate change and reducing energy consumption. As the core component of building energy conservation, the energy-saving effect of the exterior wall thermal insulation system depends not only on the thermal performance of the thermal insulation material itself, but also on the construction quality of the thermal insulation board splicing nodes. As a weak part of the thermal insulation system, the joint link is both the main channel of building heat loss and the key gap for rainwater and moisture infiltration, and its construction quality directly affects the overall efficiency and service life of the thermal insulation system[1].

Traditional thermal insulation board joint schemes mostly adopt physical splicing forms such as flat fitting or simple concave-convex tongue-and-groove, with auxiliary materials such as sealant and foam strips to treat plate joints[2]. Such schemes lack precise positioning control means and long-term sealing protection design, and problems such as plate joint dislocation and poor sealing are prone to occur in construction due to human operation errors, thus forming cold and hot bridges and leading to a sharp attenuation of the thermal performance of the thermal insulation system. At the same time, the plate joint sealing auxiliary materials of traditional joint schemes are prone to aging and cracking with the use time, and the infiltration of rainwater and moisture will cause the thermal insulation material to be damp and the thermal conductivity to rise, which not only reduces the energy-saving effect, but also seriously shortens the service life of the thermal insulation system[3].

Under the background of the continuous improvement of building energy efficiency standards and the rapid development of modular construction technology, the new lightweight composite thermal insulation structural component for civil air defense construction has innovatively developed the TG tenon-groove intelligent joint scheme. By integrating physical structural engagement, intelligent precision control and anti-leakage protection, it solves the technical pain points of traditional joint schemes from both design and construction levels. Drawing on the quantitative evaluation method of building exterior wall thermal insulation and energy-saving technology, this paper carries out research around the actual application effect of the joint scheme, compares the technical characteristics, thermal performance and energy-saving benefits of the new TG tenon-groove intelligent joint scheme with traditional joint schemes, aiming to clarify the application value of the new joint scheme and provide theoretical and practical basis for the technological upgrading of building thermal insulation engineering.

2. Core Technical Characteristics of the Comparative Research Objects

Excluding the interference of the performance differences of the thermal insulation materials themselves, this comparative study takes the most widely used traditional joint schemes and the new TG tenon-groove intelligent joint scheme in building thermal insulation engineering as the research objects, focuses on the structural design, construction control and protection system of the joint schemes, and clarifies the core technical characteristics of the two types of schemes, laying a foundation for the subsequent comparison of energy-saving effects.

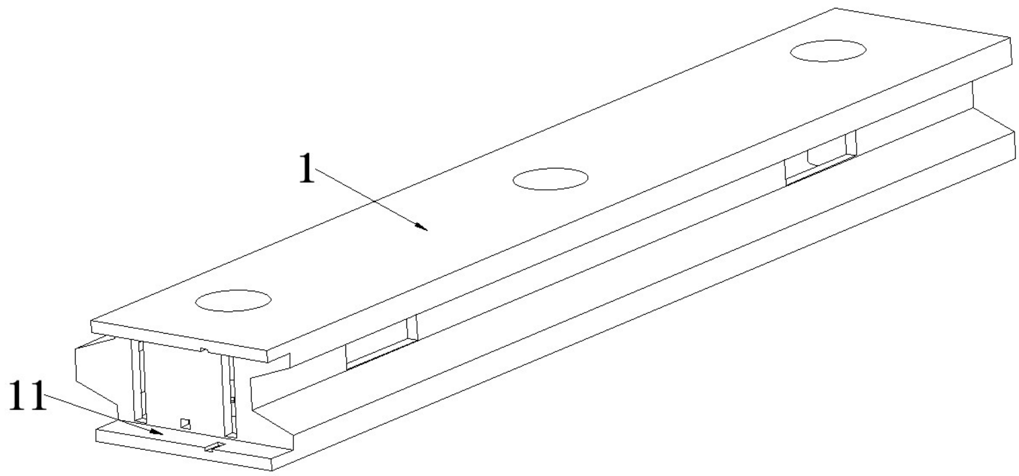

Fig. 1 New type of lightweight composite thermal insulation structural component

The TG tenon-groove intelligent joint scheme of the new lightweight composite thermal insulation structural component takes modular integrated design as the core, integrating the shell, positioning module, induction module, fool-proof module and anti-leakage module, realizing the precision, standardization and long-term effectiveness of thermal insulation board joint. The scheme adopts a TG tenon-groove type concave-convex occlusal physical joint structure, which improves the splicing tightness from the structural level by increasing the contact area of plate joints and slows down the speed of liquid infiltration from plate joints from the source; the positioning and induction module can real-timely detect the alignment of adjacent thermal insulation boards, and the fool-proof module can block the screw holes when the thermal insulation boards are dislocated, eliminating the possibility of dislocation installation from the construction end, achieving zero error in joint accuracy and completely avoiding the formation of cold and hot bridges due to dislocation; the supporting anti-leakage module can absorb a small amount of liquid infiltrating into the plate joints, prevent the thermal insulation material from being damp and deteriorated, and maintain the stability of the thermal performance at the splicing position. At the same time, the scheme adopts factory prefabricated standardized tenon-groove structure, and the on-site construction only needs to complete occlusal splicing and mechanical fixing without additional complex plate joint treatment, with high construction efficiency and controllable quality.

Traditional thermal insulation board joint schemes take pure physical splicing as the core, without intelligent precision control and special anti-leakage protection system, mainly including two mainstream forms: flat head joint and tongue-and-groove joint. Among them, the flat head joint is the most basic application scheme, the end of the thermal insulation board is of flat design, and the plate joints are directly fitted and then filled with auxiliary materials such as silicone sealant and foam strips. The construction operation is simple but completely dependent on manual work, with high plate joint dislocation rate, easy aging and cracking of the sealant, and high probability of thermal bridge formation and water seepage risk; the tongue-and-groove joint is a slight optimization on the basis of the flat head joint, the end of the thermal insulation board is designed as a simple concave-convex tongue-and-groove structure, and the initial positioning is realized through tongue-and-groove engagement, and the plate joints still need to be filled with sealant. Although it can reduce the dislocation rate to a certain extent, the positioning accuracy is still affected by the tongue-and-groove processing quality and manual operation, and the tongue-and-groove gaps are prone to water accumulation, which still cannot fundamentally solve the problems of thermal bridges and water seepage. The common shortcomings of the two types of traditional joint schemes are that the construction accuracy depends on manual work, the sealing protection only relies on auxiliary materials, and the thermal insulation performance is prone to attenuation with the use time, ultimately leading to a great reduction in energy-saving effects.

3. Comparison of Core Performances of New and Traditional Joint Schemes

The positioning accuracy, thermal performance, impermeability and durability of the joint scheme are the key indicators affecting the energy-saving effect of the thermal insulation system. Combined with the laboratory measured data and the industry general standards of building thermal insulation engineering[4], a comprehensive quantitative comparison of the core performances of the new TG tenon-groove intelligent joint scheme with the traditional flat head and tongue-and-groove joint schemes is carried out, and the results are shown in **Table 1**.

It can be clearly seen from the data in Table 1 that there are significant differences in performance between the two types of schemes. In terms of positioning accuracy and thermal bridge control[5], the new scheme achieves 0 installation dislocation rate through the fool-proof module, and the thermal conductivity at the plate joint is consistent with the thermal insulation board body, fundamentally avoiding the additional heat loss in the joint link; while the traditional schemes have a high dislocation rate due to the lack of precise positioning means, and the plate joint thermal conductivity is much higher than that of the thermal insulation board body, becoming the main source of heat loss of the thermal insulation system.

Table 1. Comparison of Core Performances of New and Traditional Thermal Insulation Board Joint Schemes

Comparison Indexes	New TG Tenon-groove Intelligent Joint Scheme	Traditional Tongue-and-groove Joint Scheme	Traditional Flat Head Joint Scheme
Installation Dislocation Rate	0 (intelligent fool-proof control)	8%~15% (tongue-and-groove assisted positioning)	15%~30% (pure manual operation)
Plate Joint Thermal Conductivity (W/(m·K))	Consistent with the thermal insulation board body	0.10~0.20	0.15~0.30
Plate Joint Water Absorption Rate	≤0.5%	≥3%	≥5%
Sealing Durability	≥20 years	5~8 years	3~5 years
Probability of Thermal Bridge Formation	0%	60%~70%	More than 80%
On-site Construction Difficulty	Low (factory prefabrication + on-site occlusal)	Medium (manual precise alignment)	Low (no positioning requirements)
Later Maintenance Cost	Extremely low (no repair demand)	Medium (regular sealant replacement)	Extremely high (frequent maintenance and repair)

In terms of impermeability and durability, the new scheme relies on the TG tenon-groove structure and anti-leakage module to achieve low water absorption rate and long-term sealing without the risk of aging and failure; the traditional schemes have a high plate joint water absorption rate, the sealing auxiliary materials are prone to aging and deformation, and the sealing durability is short, and the performance of the thermal insulation material will decline due to water seepage in the later use period. In terms of construction and maintenance, although the new scheme has standardized requirements for the processing of the tenon-groove of the thermal insulation board, the on-site construction difficulty is low, and there is no cost of thermal bridge maintenance and plate joint sealing repair in the later period, with significantly higher comprehensive cost performance than the traditional schemes.

4. Quantitative Analysis of Energy-Saving Effects of New and Traditional Joint Schemes

Drawing on the quantitative evaluation methods of energy consumption simulation and on-site measurement of building exterior wall thermal insulation and energy-saving technology[6], a high-rise residential project in a severe cold area in northern China is selected as the application scenario, and 80mm thick XPS board is used as the thermal insulation material (thermal conductivity 0.030W/(m·K)). Under the premise of the same building scale, the same climatic conditions and the same use demand, the actual energy-saving effects of the new and traditional joint schemes are quantitatively calculated and on-site monitored, excluding the interference of other factors on the energy-saving effects to ensure the objectivity of the comparison results.

4.1 Calculation of Heat Loss of Plate Joint Thermal Bridge

The building thermal engineering calculation software is used to calculate the heat flux density and the annual heat loss per unit area at the plate joints of each scheme. The results show that the plate joint heat flux density of the new TG tenon-groove intelligent joint scheme is only 0.25 W/㎡, and the annual heat loss per unit area is 1.82 kWh/㎡·a; the heat flux density of the traditional tongue-and-groove joint scheme is 0.98 W/㎡, and the annual heat loss per unit area is 7.12 kWh/㎡·a, with

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the proportion of additional heat loss reaching 291% compared with the new scheme; the heat flux density of the traditional flat head joint scheme is 1.56 W/㎡, and the annual heat loss per unit area is 11.32 kWh/㎡·a, with the proportion of additional heat loss as high as 522% compared with the new scheme.

It can be seen that due to the formation of thermal bridges, the heat loss in the joint link of the traditional joint schemes is much higher than that of the new scheme, among which the heat loss problem of the flat head joint scheme is the most prominent, which is also one of the core reasons for the poor energy-saving effect of the traditional thermal insulation system.

4.2 On-site Monitoring of Actual Engineering Energy Consumption

Three high-rise residential buildings with the same house type and area in a northern city are selected, which are constructed by adopting the new TG tenon-groove intelligent joint scheme, the traditional tongue-and-groove joint scheme and the traditional flat head joint scheme respectively. The energy consumption of the buildings during a complete heating season and cooling season after reconstruction is real-timely monitored, and the monitoring results are shown in Table 2.

Table 2. On-site Energy Consumption Monitoring Results of Buildings with Various Joint Schemes

Joint Scheme	Energy Consumption per Unit Area in Heating Season (kWh/㎡)	Energy Consumption per Unit Area in Cooling Season (kWh/㎡)	Annual Comprehensive Energy Consumption per Unit Area (kWh/㎡)	Proportion of Energy Consumption Increase Compared with the New Scheme
New TG Tenon-groove Intelligent Joint Scheme	12.56	8.23	20.79	—
Traditional Tongue-and-groove Joint Scheme	13.89	9.05	22.94	10.3%
Traditional Flat Head Joint Scheme	15.12	9.88	25.00	20.2%

The monitoring data show that the energy consumption of the buildings adopting the new joint scheme is the lowest in both the heating season and the cooling season, the annual energy consumption of the buildings with the traditional tongue-and-groove joint scheme is 10.3% higher than that of the new scheme, and that of the traditional flat head joint scheme is 20.2% higher. The core reason for the significantly high energy consumption of the buildings with traditional joint schemes is that the plate joint thermal bridge leads to the intensified loss of indoor cold and heat load, and the building heating and refrigeration systems need to consume more energy to maintain the set indoor temperature. This increase in energy consumption is not caused by the insufficient performance of the thermal insulation material itself, but by the poor construction quality and protection effect of the joint link, which further confirms the importance of optimizing the joint scheme to improve the overall energy-saving effect of the building thermal insulation system.

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4.3 Analysis of Energy-Saving Benefits in the Whole Life Cycle

Taking the design service life of the building thermal insulation system as the cycle, combined with the residential electricity price in northern China and the industry market price of building thermal insulation engineering, the energy consumption cost, construction cost, later maintenance cost and system replacement cost are comprehensively considered to calculate the energy-saving benefits of the new and traditional joint schemes in the whole life cycle. Among them, the new scheme is calculated according to the 20-year service life, the traditional tongue-and-groove joint scheme according to 8 years, and the traditional flat head joint scheme according to 5 years, all converted into the total cost for 20 years for comparison.

The calculation results show that the total 20-year energy consumption cost per unit area of the new TG tenon-groove intelligent joint scheme is 232.85 CNY/㎡, the construction, maintenance and replacement cost is 86.50 CNY/㎡, and the total 20-year cost is 319.35 CNY/㎡; the total 20-year energy consumption cost per unit area of the traditional tongue-and-groove joint scheme is 256.80 CNY/㎡, the construction, maintenance and multiple replacement cost is 158.20 CNY/㎡, and the total 20-year cost is 415.00 CNY/㎡, an increase of 29.9% compared with the new scheme; the total 20-year energy consumption cost per unit area of the traditional flat head joint scheme is 279.40 CNY/㎡, the construction, maintenance and replacement cost is as high as 225.80 CNY/㎡, and the total 20-year cost is 505.20 CNY/㎡, an increase of 58.2% compared with the new scheme.

Although the initial processing and construction cost of the thermal insulation board of the new TG tenon-groove intelligent joint scheme is slightly higher than that of the traditional schemes, due to the long service life of the system, no frequent maintenance and replacement in the later period, and the continuous reduction of energy consumption cost, the comprehensive cost in the whole life cycle is much lower than that of the traditional joint schemes, with significant long-term economic and energy-saving benefits.

5. Application Adaptation and Technological Innovation Value of Joint Schemes

5.1 Application Scenario Adaptation of Different Joint Schemes

Combined with the technical characteristics, performance performance and energy-saving effects of the new and traditional joint schemes, there are significant differences in the applicable scenarios of various schemes. The engineering selection needs to be comprehensively considered in combination with the positioning, use demand, climatic characteristics and budget level of the construction project to ensure that the joint scheme matches the actual project and achieve a balance between energy-saving effects and economic benefits.

The new TG tenon-groove intelligent joint scheme is suitable for construction projects with high requirements for thermal insulation accuracy, durability and energy-saving effects, such as civil air defense projects, high-end residential buildings, commercial complexes, industrial buildings, etc. It is also suitable for climatic regions with special requirements for thermal performance and impermeability such as severe cold areas in the north and humid areas in the south. Such projects have high requirements for the long-term stability of the building thermal insulation system, and the long-term energy-saving and low maintenance advantages of the new scheme can be fully exerted.

The traditional tongue-and-groove joint scheme can be applied to civil residential projects with certain requirements for energy-saving effects and medium budget, and is more suitable for inland areas with relatively mild climate and less rainwater. The building thermal insulation system in such areas is less affected by water seepage, and the basic positioning and sealing of the tongue-and-groove joint can meet the basic energy-saving needs. The traditional flat head joint scheme is only suitable for temporary buildings, simple factories, low-budget people's livelihood projects and other projects with low requirements for the service life and energy-saving effects of the thermal insulation system.

Such projects have short construction periods and limited service life, and the advantages of low cost and easy construction of the flat head joint can be reflected.

5.2 Technological Innovation and Industry Value of the New Joint Scheme

The research and development and application of the new TG tenon-groove intelligent joint scheme have broken through the limitations of the traditional thermal insulation board joint scheme of "manual operation and passive sealing"[7], and realized multiple innovations in the building thermal insulation board joint technology. Its core innovation points are reflected in four aspects: structural design, precision control, protection system and construction technology. In terms of structural design, the TG tenon-groove type concave-convex occlusal replaces the traditional flat splicing, which improves the sealing performance and splicing stability from the structural level and reduces the plate joint heat loss and water seepage channels; in terms of precision control, the positioning, induction and fool-proof modules are integrated to realize the intelligent management and control of joint accuracy and eradicate the thermal bridge problem caused by human errors from the construction end; in terms of protection system, the structural sealing is combined with active anti-leakage, and the anti-leakage module is used to absorb the infiltrated liquid to avoid the damp of thermal insulation materials and maintain the long-term stability of the thermal performance of the system; in terms of construction technology, the factory prefabricated standardized tenon-groove and functional modules are adopted for on-site integrated assembly, promoting the transformation of thermal insulation board joint from manualization to industrialization and standardization, and improving the construction quality and efficiency.

From the perspective of industrial development, the technological innovation of the new joint scheme has important industrial value. First, the scheme greatly reduces the heat loss of the thermal bridge in the joint link, directly improves the overall energy-saving effect of the building thermal insulation system, helps buildings achieve low energy consumption or even nearly zero energy consumption goals, and meets the national policy requirements of energy conservation and emission reduction and building energy conservation. Second, the scheme solves the common quality problems of the industry such as thermal insulation board joint dislocation and sealing failure, improves the construction quality and stability of building thermal insulation engineering, reduces the engineering rework caused by plate joint problems in the later period, and lowers the engineering management cost. Third, the scheme provides new ideas for the innovation of building thermal insulation technology, promotes the development of building thermal insulation engineering from the single performance optimization of materials to the integrated optimization of materials, structure, construction and control, and helps the building energy conservation industry move towards high quality and long-term effectiveness.

6. Conclusion

The quality control of the thermal insulation board joint link is the key to improving the energy-saving effect of the building exterior wall thermal insulation system. Through the systematic comparative study on the TG tenon-groove intelligent joint scheme of the new lightweight composite thermal insulation structural component and the traditional thermal insulation board joint schemes, this paper clarifies that the positioning accuracy and sealing durability of the joint scheme are the core factors affecting the energy-saving effect of the thermal insulation system. The traditional joint schemes are important reasons for the decline of the energy-saving effect of the building thermal insulation system due to the lack of precise positioning control and long-term sealing protection design, large construction errors, high probability of thermal bridge formation and rapid attenuation of thermal insulation performance.

The new TG tenon-groove intelligent joint scheme integrates TG tenon-groove structural engagement, intelligent fool-proof positioning and anti-leakage module supporting, realizes zero error in joint accuracy, zero probability of thermal bridge formation and long-term leakage protection, solves the technical pain points of traditional joint schemes from both design and construction levels, reduces the plate joint heat loss by 65%~85% compared with traditional schemes, reduces the annual comprehensive energy consumption of supporting buildings by 8%~20%, and the comprehensive cost in the whole life cycle is much lower than that of traditional schemes, with significant energy-saving and economic benefits.

The TG tenon-groove intelligent joint scheme of the new lightweight composite thermal insulation structural component provides an effective path for the upgrading of building thermal insulation board splicing technology. In the future, it can be optimized and promoted in various aspects: first, carry out material integration optimization, integrate thermal insulation, fire prevention and waterproof functions into the TG tenon-groove structure, develop a multi-functional integrated tenon-groove joint module, and further improve the comprehensive performance of the joint node; second, promote intelligent upgrading, integrate the Internet of Things technology and add temperature and humidity sensors in the joint module to realize real-time monitoring and early warning of plate joint status and build an intelligent perception thermal insulation joint system; third, accelerate the standardization promotion, formulate industry standards and construction specifications for the TG tenon-groove type thermal insulation board joint scheme, reduce the processing and on-site construction cost of the thermal insulation board tenon-groove, and promote its large-scale application; fourth, expand the cross-scenario adaptability, optimize the size and specification of the TG tenon-groove structure to adapt to various thermal insulation materials such as EPS, XPS, rock wool and PU, and further expand the application scope in civil buildings, industrial buildings, municipal engineering and other scenarios.

The development of building energy-saving technology needs to start from every technical node. The optimization of the thermal insulation board joint scheme seems to be a detailed improvement of building thermal insulation engineering, but it can effectively improve the overall energy-saving effect and service life of the thermal insulation system. The application of the new TG tenon-groove intelligent joint scheme not only provides a new choice for the scheme selection of building thermal insulation engineering, but also promotes the development of building thermal insulation technology towards integration, intelligence and long-term effectiveness, which has important practical significance for achieving the energy conservation and emission reduction goals in the construction field.

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