

Article

Thermal Deformation of External Wall Insulation Systems Using EPS, XPS and PU Boards: A Combined Numerical and Experimental Study

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Abstract

Under extreme steady-state temperature gradients, external thermal insulation composite systems (ETICSs) are prone to thermal deformation, which can cause mortar cracking, hollowing, and even delamination and detachment of insulation boards, thus degrading building envelope performance and threatening structural and personal safety. In this study, a combined method of numerical simulation using ANSYS software and experimental testing was adopted to investigate the thermal deformation characteristics of three commonly used insulation materials: Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), and Polyurethane (PU). The effects of temperature difference from 10 °C to 30 °C, insulation board thickness from 30 mm to 100 mm, and surface mortar thickness from 5 mm to 10 mm on strain distribution and deformation mechanism were systematically analyzed. Experimental validation showed good agreement with the simulation results, quantified by an estimated relative error of less than 15% across the investigated insulation thicknesses and steady-state temperature conditions. The results indicate that the strains of EPS, XPS, and PU boards all increase significantly as the temperature difference across the board rises. Under outdoor temperatures of 30 °C, 40 °C and 50 °C with a constant indoor temperature of 20 °C, the thickness-direction strain at the EPS–mortar interface increases by approximately 35% when the temperature difference increases from 10 °C to 30 °C. Increasing both insulation board thickness and mortar protective layer thickness effectively reduces thermal deformation. Specifically, when the EPS board thickness increases from 30 mm to 100 mm, the thickness-direction strain decreases by approximately 73%; and when the mortar thickness increases from 5 mm to 10 mm, the interfacial strain decreases by approximately 32%. Due to differences in linear expansion coefficients, the three insulation materials exhibit distinctly different thermal deformation behaviors, with the thickness-direction strain following the order EPS > XPS > PU. These findings provide a theoretical basis and data support for material selection, structural optimization, and safety design of external wall insulation systems.



Academic Editors: Antonio Caggiano and Apple L.S. Chan

Received: 9 May 2026

Revised: 11 June 2026

Accepted: 24 June 2026

Published: 29 June 2026

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Keywords: external thermal insulation composite systems (ETICSs); thermal strain; interfacial stress; numerical simulation; insulation board

1. Introduction

Exterior insulation composite systems (ETICSs) are widely used to improve the energy efficiency of buildings. However, under extreme steady-state temperature gradients, a

large temperature differential may occur inside the insulation board. Because different materials in ETICSs have different coefficients of thermal expansion, elastic modulus, and thermal conductivity, inhomogeneous thermal expansion and contraction can be caused. The resulting thermal deformation may generate significant interfacial stresses, resulting in cracking, hollowing of the surface mortar, even leading to system debonding. This structural deterioration reduces the thermal performance of the building envelope and may threaten public safety if the surface layer falls off.

Numerous researchers have documented the temperature field distributions and system durability across varying climates and configurations. Recently, Chandrasiri, D et al. [1] investigated the thermal efficiency of light-gauge steel panels with varying insulation ratios using numerical models, demonstrating the strong dependence of thermal transmittance on insulation placement. Wang, J et al. [2] evaluated the weathering resistance of prefabricated thermal insulation walls, noting the significant impact of temperature stress on the concrete–insulation interface. Huang Z et al. [3] used ANSYS software to study and numerically simulate the durability of the external wall insulation system of buildings in hot summer and cold winter zones. Niziurska et al. [4] evaluated the effect of mineral wool (MW) partitioning on fire spread in EPS-based ETICSs, while Kumar et al. [5] and Zhu et al. [6] analyzed insulation properties and coupled thermal-moisture-mechanical models across different climatic zones. Furthermore, studies by Gao et al. [7] and Niu et al. [8] examined material degradation under specific high-temperature/humidity or freeze–thaw cyclic conditions. Recent material optimizations have also explored vacuum-insulated boards [9], ceramic nanocomposites [10], multilayered superinsulation [11], and organosilicon graphene composites [12], detailing their mechanica and thermal advantages [13].

Despite these extensive investigations into ETICS durability under natural climatic weathering and transient hygrothermal cycles, the precise evaluation of interfacial thermal strain governed strictly by steady-state temperature gradients remains largely unexplored [14]. Most existing structural assessments isolate a single material variable or rely on transient environmental cycling, leaving a distinct gap in understanding the synergistic elastic responses of the system under constant, extreme temperature differentials. For instance, while studies by Sha [15], Franzoni [16], Xiong [17], Yang [18], Ma [19], and Wu [20] monitored strain fields for specific innovative structures (e.g., foam glass, glazed hollow beads, or dense-column composite boards), and others explored global energy performance metrics [21–24], they do not systematically decouple the combined mechanical influence of core insulation material type, board thickness, and mortar protective layer thickness on the resulting interfacial strain.

Therefore, the primary objective of this research is to systematically quantify the purely elastic thermal deformation characteristics of three typical ETICS variants (utilizing EPS, XPS, and PU boards) subjected to constant, steady-state temperature gradients. Through a combined numerical and experimental framework, this study strictly addresses the research gap by evaluating how variations in plate thickness (30 mm to 100 mm), mortar thickness (5 mm to 10 mm), and material-specific linear expansion coefficients dictate the maximum thermal strain distribution at the insulation–mortar interface. The results are intended to provide validated theoretical limits to inform structural optimization and prevent thermally induced cracking in contemporary facade engineering.

2. Numerical Simulation Study on Temperature Difference Deformation of External Wall Insulation System

2.1. Mathematical Modeling of Temperature Difference Deformation of External Wall Insulation System

Finite element models of the EPS insulation system, featuring board thicknesses of 30 mm, 50 mm, and 100 mm covered with mortar thicknesses of 5 mm, 8 mm, and 10 mm, were developed using ANSYS 2021 R2 software. Numerical simulations were carried out under three temperature difference conditions of 30 °C, 20 °C and 10 °C in a high-temperature environment and 35 °C, 30 °C and 25 °C in a low-temperature environment, respectively, to obtain the distribution rule of temperature field and stress along the direction of board thickness inside the thermal insulation system. The EPS board was chosen as the primary study item and compared to two other types of boards using XPS and PU. Table 1 displays the specific numerical simulation condition.

Table 1. Numerical simulation condition.

Board	Temperature Difference/°C	Board Thickness/mm	Mortar Thickness/mm
EPS	30/35	30	5
	20/30	50	8
	10/25	100	10
XPS	30/35	30	5
PU	30/35	30	5

The following presumptions need to be followed to simplify the insulation system's changing procedure during the simulation phase.

1. Each insulation board and the cement mortar were assumed to be isotropic materials;
2. The connection between the various external wall insulation boards and the cement mortar protective layer was assumed to be ideal, meaning that there was no relative sliding between them and they did not separate;
3. This ideal assumption serves to evaluate the theoretical maximum elastic thermal stress limits developed at the interfaces prior to the onset of actual structural damage (e.g., cracking or debonding);
4. The insulation board and the wall's internal structure were assumed to be continuous media;
5. When the temperature field of the entire external wall insulation system was analyzed, it was assumed that no additional heat source will be generated inside the cement mortar protective layer and the insulation board;
6. It was assumed that the cement mortar protective layer and the insulation board would inherently maintain their structural integrity; the model specifically predicts purely elastic thermal deformation, and any actual physical damage or failure behavior under complex thermal effects is ignored.

The base wall, bonding mortar layer, insulation board layer, and plastering mortar layer were all included in the simulation model, which was primarily built using ANSYS software. Each layer had a size of 300 mm × 300 mm. The simulation model was constructed using ANSYS and modeled using DM. The basic coordinate system is displayed in Figure 1a, and the coordinates of each portion in the length direction (X direction) and breadth direction (Y direction) of the wall were (−150, 150). The parts range along the Z direction was as follows: base wall (0–100), bonding mortar layer (100–105), insulation board layer (105–135), and plastering mortar layer (135–140), in that sequence. The top

view corresponds to the negative Z direction, while the primary cross-sectional view aligns with the model's Y direction. The model diagram is displayed in Figure 1.

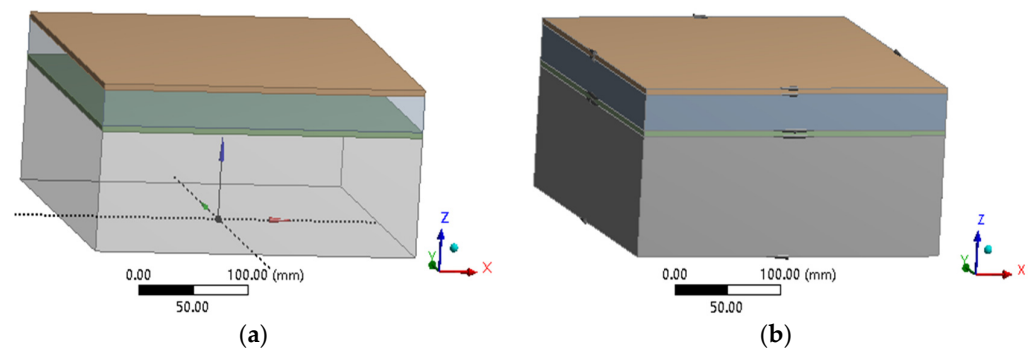


Figure 1. System model diagram. (a) Modeling model diagram; (b) Analysis model diagram.

The mesh density was suitably adjusted to ensure the calculation accuracy, to the extent possible, to save the solution time and increase the solving efficiency. A mesh sensitivity analysis was conducted, reducing the maximum element size from 10 mm to 2 mm. The results indicated that grid independence was achieved at a 5 mm mesh size, as the maximum strain deviation between successive mesh refinements fell below 2%. In Figure 2, the mesh division diagram is displayed.

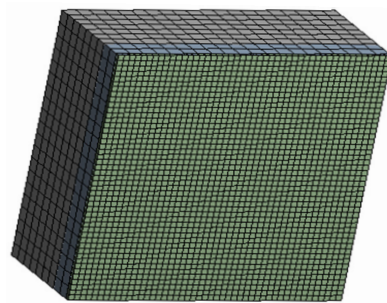


Figure 2. Meshing diagram.

The key parameters that influence the deformation analysis results of thermal insulation systems under temperature difference conditions include mass density, coefficient of linear expansion, thermal conductivity, specific heat capacity, elastic modulus, and other factors. Table 2 provides ranges for the properties of the three insulating boards.

Table 2. Summary of thermal parameters (Note: typical values are sourced directly from standard building material specifications and engineering handbooks [3,5,25]).

Material/Attribute	EPS	XPS	PU	Cement Mortar	Concrete Wall
Thermal conductivity/W/m·K	0.039	0.032	0.025	0.6	1.74
Specific heat capacity/J/kg·K	1500	1400	1380	840	900
Elastic modulus/MPa	9.5	10	60	20,000	25,000
Poisson ratio	0.37	0.32	0.47	0.2	0.2
Density/kg/m ³	20	35	45	1800	2430
Coefficient of linear expansion/1/°C	2.3×10^{-5}	1.3×10^{-5}	1.1×10^{-5}	1×10^{-5}	1×10^{-5}

Two boundary conditions were set on the external surface of the mortar and the base wall closed to the interior side for high ambient temperature contrast and low ambient

temperature contrast, as indicated in Table 3. Convective heat transfer coefficients were set to $25 \text{ W}/(\text{m}^2 \cdot \text{K})$ for the external outdoor surface and $8 \text{ W}/(\text{m}^2 \cdot \text{K})$ for the internal indoor surface. With a low temperature of -15°C on behalf of the outdoor ambient temperature of -15°C , and with the room temperature stabilized at 20°C , the low-temperature environment has 35°C temperature difference conditions; with a high temperature of 50°C on behalf of the outdoor ambient temperature of 50°C , and with the room temperature stabilized at 20°C , the high-temperature environment has 30°C temperature difference conditions.

Table 3. Temperature boundary conditions.

Temperature Boundary Condition	High-Temperature Environment	Low-Temperature Environment
Outdoor temperature/ $^\circ\text{C}$	50	-15
	40	-10
	30	-5
Indoor temperature/ $^\circ\text{C}$	20	20

2.2. Governing Finite Element Formulations for Thermal Deformation Analysis

The thermal deformation analysis of the external thermal insulation composite system (ETICS) involves a sequentially coupled thermal-mechanical approach, consisting of temperature field computation followed by a structural strain solution within the ANSYS environment.

1. Governing Equations for the Temperature Field

Based on the relationship between temperature and time, the temperature field analysis is categorized into steady-state and transient thermal analyses. In a steady-state thermal analysis, the temperature of any node does not vary with time, and its energy balance equation is expressed as:

$$[K_c]\{T\} = \{Q\} \quad (1)$$

where $[K_c]$ is the thermal conductivity matrix, $\{T\}$ is the nodal temperature vector, and $\{Q\}$ is the heat flow rate vector.

For transient processes where thermal boundary conditions or internal energies change significantly with time, the transient heat balance equation is expressed in matrix form as:

$$[C]\{\dot{T}\} + [K_c]\{T\} = \{Q\} \quad (2)$$

where $[C]$ is the specific heat matrix, and $\{\dot{T}\}$ is the time derivative of temperature.

2. Finite Element Formulation for Thermal Strain and Deformation

For an isotropic rectangular element within the multi-layered ETICS model, the free thermal strain vector $\{\epsilon_0\}$ induced by a uniform temperature change ΔT relative to the reference temperature is defined as:

$$\{\epsilon_0\} = [\alpha\Delta T, \alpha\Delta T, \alpha\Delta T, 0, 0, 0]^T \quad (3)$$

where α is the coefficient of linear expansion of the respective layer material (e.g., EPS, XPS, PU, or mortar).

In the structural finite element analysis implemented in this study, the total nodal displacements and subsequent strains are solved using the structural displacement method. The governing finite element equilibrium equation under thermal loading is expressed as:

$$[K_s]\{u\} = \{F\} + \{F_{th}\} \quad (4)$$

where $[K_s]$ is the structural stiffness matrix; $\{u\}$ is the nodal displacement vector; F is the external mechanical nodal force vector; and $\{F_{th}\}$ is the structural temperature nodal load array.

The thermal load array $\{F_{th}\}$ is computed by integrating the initial thermal strains over the element volume V :

$$\{F_{th}\} = \int_V [B]^T [D] \{\epsilon_0\} dV \quad (5)$$

where $[B]$ is the strain–displacement matrix, and $[D]$ is the elastic stress–strain material matrix governed by the elastic modulus (E) and Poisson’s ratio (ν) reported in Table 2. Since no external mechanical forces are applied to the boundaries of the insulation system in this study ($\{F\} = 0$), Equation (4) simplifies to:

$$[K_s]\{u\} = \{F_{th}\} \quad (6)$$

Through Equation (6), the non-uniform temperature field derived from Equations (1) or (2) is directly converted into nodal thermal structural loads, yielding the structural displacement $\{u\}$ and the localized multi-directional interfacial thermal strains ($\epsilon_x, \epsilon_y, \epsilon_z$) evaluated in the Results section.

3. Experiments and Methods

To investigate the deformation of the external wall insulation system test, the experimental platform was constructed and the three different types of EPS, XPS, and PU heat preservation material specimens of the external wall insulation system were created. The experimental platform is shown in Figure 3. The temperature tester was used to read the distribution of the temperature field inside the specimen; the thermostatic test chamber had a controllable temperature, which was used to create the outdoor environment as well as the indoor environment required for the test (constant temperature of 20 °C).

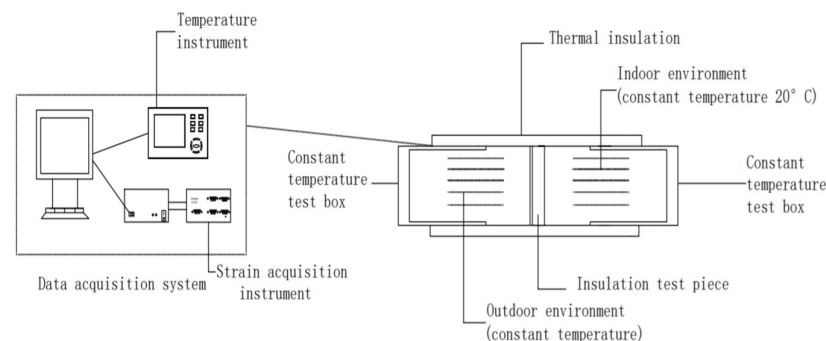


Figure 3. Schematic diagram of the experimental platform (dimensions in mm, temperature in °C).

3.1. Experimental Materials and Instruments

The experimental materials were: EPS board, XPS board, PU board, anti-cracking mortar, and mesh cloth. The specific parameters of the various experimental materials are shown in Table 4.

The experimental instruments were: programmable constant temperature and humidity test chamber, strain collection and analysis system, resistance strain gauges, temperature recorder, T-type thermocouple, and K-type thermocouple. The specific parameters of the various experimental instruments are shown in Table 5.

Table 4. Details of experimental materials.

Name	Brand	Specification
EPS board	Miao Lingmai	L 300 mm × W 300 mm × H 30 mm
XPS board	Miao Lingmai	L 300 mm × W 300 mm × H 30 mm
PU board	Miao Lingmai	L 300 mm × W 300 mm × H 30 mm
Glass fiber mesh	Zefeng	1 m × 50 m
Anti-crack mortar	Wan Xinda	50 kg ± 0.5 kg

Table 5. Details of experimental instruments.

Name	Manufacturer	Specification	Precision	Range
Programmable constant temperature and humidity test chamber	Dongguan Precision Environmental Test Equipment Co. Dongguan, China	TY/HWHS-50L	±0.1 °C	−20–80 °C
Strain collection and analysis system	Dongguan Jingyan Instrument Technology Co. Dongguan, China	DH3821	0.3%	0~±19,999 $\mu\epsilon$
Resistance strain gauges	-	-	±1%	Strain 0–20,000 $\mu\text{m}/\text{m}$
Temperature recorder	Hangzhou Huipu Instrument Co. Hangzhou, China	TCP-XL + CH	0.5%	−200–1300 °C
T-type thermocouple	-	T-shape	0.4%	−200–260 °C
K-type thermocouple	-	GG-K–30-SLE	0.4%	−200–482 °C

3.2. Experimental Setup

The width and height of the thermal insulation board should not exceed 1200 mm and 600 mm respectively, following the actual project's application and the Technical Regulations for External Thermal Insulation Engineering of External Walls [26]. The thermal insulation board's standard dimensions are 600 mm in length and width. Simultaneously taking into account the experiment box size, as temperature conduction during the experimental process was restricted, and to prevent material waste, the length and width of the 300 × 300 mm insulation board was chosen, and the structural design of the specimen is shown in Figure 4.

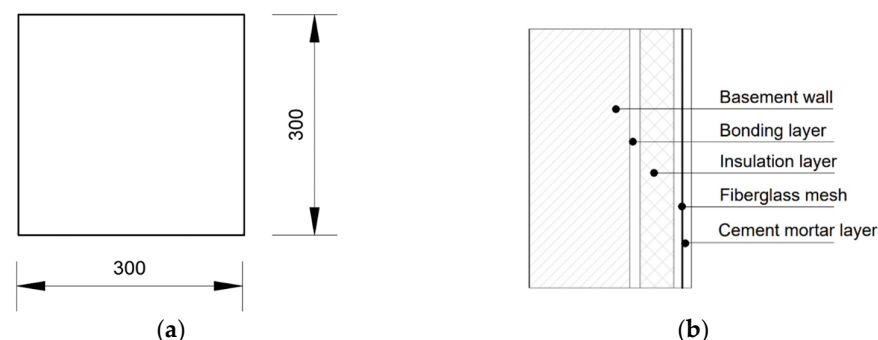


Figure 4. Design drawing of external insulation structure specimen (dimensions in mm). (a) Ichnography; (b) Elevation.

The insulation board was cut to the required dimensions of 300 mm × 300 mm, an even layer of anti-cracking mortar was applied to the surface of the board, and a layer of 300 mm × 300 mm alkali-resistant fiberglass mesh cloth was laid. Finally, another layer of anti-cracking mortar was applied to form a protective layer of cement mortar, which was smoothed out to control the mortar's thickness, which was adjusted to be 5 mm, 8 mm, or 10 mm, depending on the test conditions. The experimental conditions matched the

simulation conditions. In the configuration seen in Figure 5, thermocouples and resistance strain gauges were placed inside the specimen. The temperature and strain at this point were recorded when the surrounding sides' temperatures stopped fluctuating. The average value of the data of each measurement point in each layer was selected as the measured value of each layer to compare with the numerical simulation value.

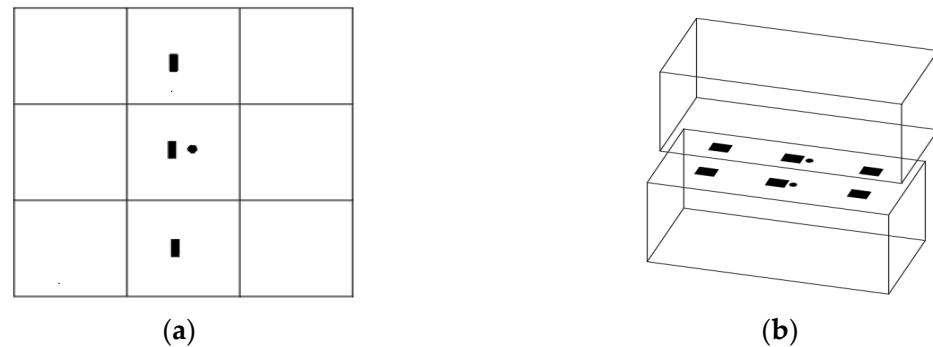


Figure 5. Location of measurement points. (a) Board thermocouple strain gauge arrangement diagram; (b) Arrangement of thermocouple strain gauges per layer inside the board.

3.3. Validation Protocol

To systematically verify the precision of the finite element model prior to extensive parametric simulation, an explicit validation protocol was established. Experimental strain and temperature measurements were meticulously compared with the corresponding nodal values extracted from the ANSYS simulations at identical spatial coordinates within the test specimens. The comparison rigorously utilized the relative error metric, calculated as the absolute difference between the simulated and measured values divided by the measured value. An acceptable error threshold of 15% was predefined to indicate good agreement between the experimental observations and the linear elastic numerical predictions; this threshold mathematically accounts for the inherent microstructural heterogeneity and practical boundary variances present in physical mortar and insulation samples.

4. Results and Discussion

4.1. Preliminary Temperature Field and Deformation Analysis

The temperature distribution along the wall thickness direction is shown in Figure 6; the specific temperature for the mortar surface was set as high temperatures of 50 °C, 40 °C, 30 °C, low temperatures of −15 °C, −10 °C, −5 °C, and the indoor side was 20 °C. The base wall layer was 0–100 mm, the bonding mortar layer was 100–105 mm, the insulating board layer was 105–135 mm, and the plastering mortar layer was 135–140 mm.

The temperature distribution curve trend was smooth and transitional when the outside ambient temperature boundary conditions fell between 30 °C and 50 °C and between −15 °C and −5 °C. When the thickness of the insulation system was taken into account, the temperature change within the base concrete wall and the bonding layer was minimal, fluctuating within a range of less than 3 °C. In contrast, the temperature change within the insulation board was significant, and the temperature change within the insulation system only occurred in the direction of the wall's thickness and did not occur in the direction of the wall's height or width.

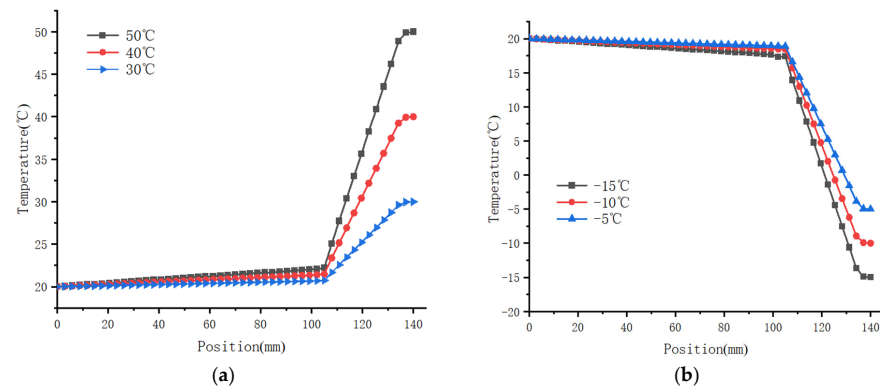


Figure 6. Temperature distribution along the wall thickness direction. (a) The temperature distribution along the thickness of the wall in a high-temperature environment; (b) The temperature distribution along the thickness of the wall in a low-temperature environment.

Under actual engineering conditions, the insulation boards work under temperature differential conditions. In the summer period, the thin plaster outside the insulation system is in a high-temperature environment with heat build-up of up to 50 °C. The walls inside the system are in a lower ambient temperature of about 20 °C, which results in a large temperature difference between the two sides of the system. Due to the thin plaster and base wall thermal conductivity being large, the temperature is quickly transferred to both sides of the insulation board, resulting in the existence of a temperature difference between the two sides of the insulation board. In winter conditions, the insulation system outside is colder, down to −15 °C, and the interior is more habitable, where the temperature is generally 20 °C or so; which also forms a temperature difference, because the system of different materials with different thermal conductivities will lead to the formation of the temperature difference in the insulation board on both sides.

Under this temperature difference condition, an uneven temperature field will be generated inside the insulation board and wall system, and the insulation board will warp and change, which will cause the insulation board to fall off in serious cases. The temperature difference between the two sides of the insulation board was greater than theirs due to the insulation board's lower thermal conductivity. This significant temperature gradient across the insulation board is clearly reflected by the steep slope in the temperature distribution curve in Figure 6, whereas the profiles within the base wall and mortar remain relatively flat. Since the base concrete wall's temperature barely changed at all, it was reasonable to anticipate that the base concrete wall would bend very little, if at all, during the ANSYS simulation of the insulated board's temperature differential deformation. Consequently, the concrete base wall could be disregarded throughout the simulation and experimental phases, and the deformation of the insulation system made up of insulation board and thin plaster mortar could only be taken into account when the insulation board next to the wall side was fully secured by the three-way constraint.

From the analysis of the two deformation cloud diagrams caused by the high and low temperature differentials, whether high temperature or low temperature, the larger the temperature difference between the outside and indoor environments, the greater the induced thermal deformation in the insulation system.

4.2. Deformation Results of External Wall Insulation System Under Different Temperature Differences

The EPS insulation board had a thickness of 30 mm, covered in 5 mm cement mortar composed of a thermal insulation system. In high-temperature scenarios, the outdoor ambient temperature was chosen to be 50 °C, and the room temperature was stabilized at 20 °C;

in low-temperature scenarios, the outdoor ambient temperature was chosen to be $-15\text{ }^{\circ}\text{C}$, and the room temperature was stabilized at $20\text{ }^{\circ}\text{C}$; the deformation cloud diagram of the insulation board derived from the simulation is shown in Figure 7. From the simulation results, when the temperature was $30\text{ }^{\circ}\text{C}$, the maximum deformation of the insulation board was 0.0408 mm ; when the temperature was $40\text{ }^{\circ}\text{C}$, the maximum deformation of the insulation board was 0.0514 mm ; when the temperature was $50\text{ }^{\circ}\text{C}$, the maximum deformation of the insulation board was 0.0614 mm . In the case of high temperatures, the higher the temperature, the greater the effect on the temperature deformation of the insulation system. When the temperature was $-5\text{ }^{\circ}\text{C}$, the maximum deformation of the insulation board was 0.0510 mm ; when the temperature was $-10\text{ }^{\circ}\text{C}$, the maximum deformation of the insulation board was 0.0614 mm ; when the temperature was $-15\text{ }^{\circ}\text{C}$, the maximum deformation of the insulation board was 0.0718 mm . In the case of low temperatures, the lower the temperature, the greater the effect on the deformation of the insulation system.

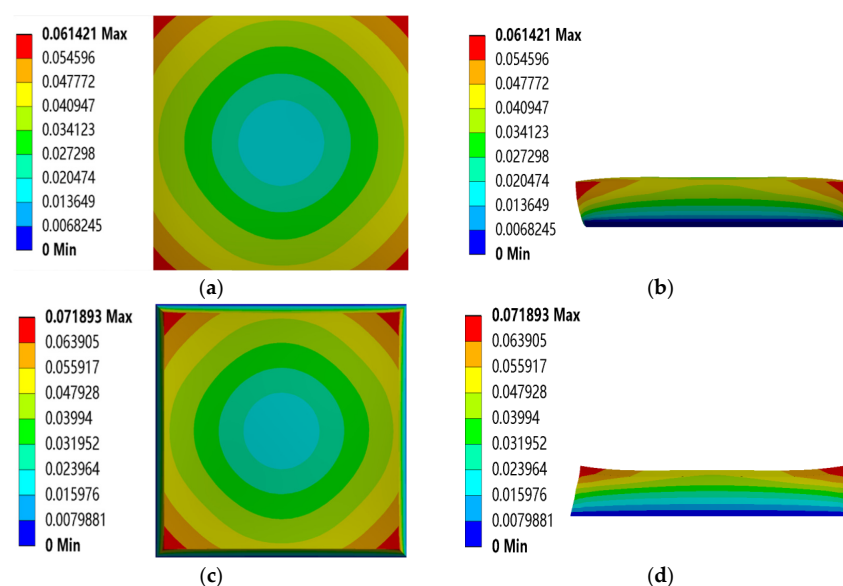


Figure 7. Cloud diagram of insulation board deformation (X and Y denote the in-plane longitudinal and transverse directions of the board, respectively, while Z denotes the out-of-plane thickness direction). (a) 30 mm thick $50\text{ }^{\circ}\text{C}$ EPS top view; (b) 30 mm thick $50\text{ }^{\circ}\text{C}$ EPS main view; (c) 30 mm thick $-15\text{ }^{\circ}\text{C}$ EPS top view; (d) 30 mm thick $-15\text{ }^{\circ}\text{C}$ EPS main view.

As shown in the top views of Figure 7a,c, since the outdoor ambient temperature acted uniformly on the insulation board and the shape of the insulation board was homogeneous, the deformation of the insulation board changed symmetrically under the action of the temperature along the direction of the width and length of the insulation board. Simulations was a simulation only in the bottom of the board set constraints; the board edge deformation was not constrained; if the board displaces around the set constraints, the insulation board edge temperature under the action of the expansion and contraction of deformation would be limited; the insulation board in the temperature stress under the influence of the deformation of the maximum location would also change. Figure 7b,d show that the deformation along the board thickness direction was not uniform because the board was below the fixed constraints and temperature. At an outdoor high temperature of $50\text{ }^{\circ}\text{C}$, the upper part of the board expanded outward due to the role of the high temperature, and at a low temperature of $-15\text{ }^{\circ}\text{C}$, the upper part of the board contracted due to the role of the low temperature. The deformation gradually decreased from top to bottom.

The distribution of temperature difference deformation of the 30 mm thick EPS thermal insulation board, covered in 5 mm of cement mortar to form the thermal insulation system,

is shown in Figure 8 in both the $-15\text{ }^{\circ}\text{C}$ and $50\text{ }^{\circ}\text{C}$ outdoor environments, with the room temperature stabilized at $20\text{ }^{\circ}\text{C}$. The thickness of the insulation board was 0–30 mm, and 30–35 mm was the thickness of the cement mortar. From Figure 8a,b, the maximum strain in the X, Y direction was close to 4.2×10^{-5} when the insulation system was subjected to a temperature of $50\text{ }^{\circ}\text{C}$, while the minimum strain on the side closest to the interior was approximately 1.5×10^{-5} . From Figure 8d,e, the insulation system was subjected to a temperature of $-15\text{ }^{\circ}\text{C}$, the maximum strain in the X, Y direction was close to -5.3×10^{-5} and the minimum strain was -1.6×10^{-5} . The magnitude of the strain in the X and Y directions increased gradually with the thickness of the insulation system, and the strain was smaller on the side near the interior due to smaller temperature changes and constraint limitations. The measured strain curves in the X and Y directions were close to each other, the continuity of each layer of the board was affected in the test, which led to the influence of the board temperature conduction, there was little difference in the measured strain curves along the thickness of the board in the X and Y directions, and the overall curves were the same with the simulation rule.

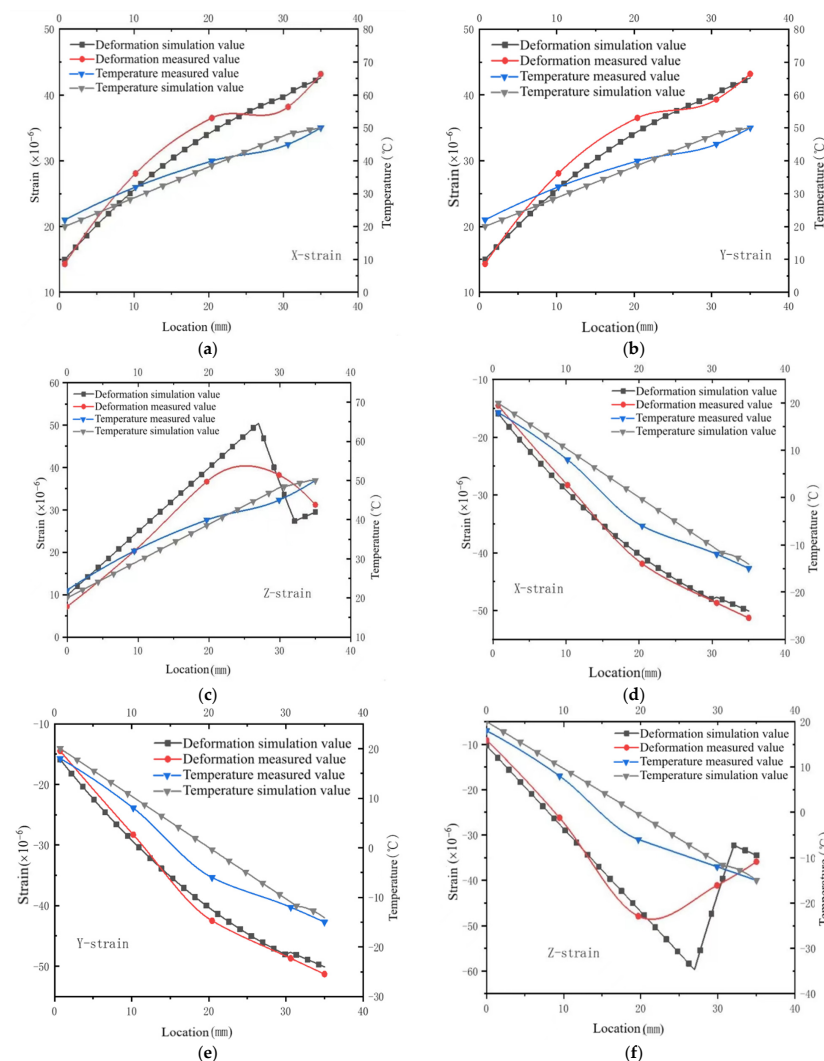


Figure 8. Temperature difference deformation distribution of insulation system along the board thickness in each direction at $50\text{ }^{\circ}\text{C}$ and $-15\text{ }^{\circ}\text{C}$. (a) Distribution of deformation in X directions at $50\text{ }^{\circ}\text{C}$; (b) Distribution of deformation in Y directions at $50\text{ }^{\circ}\text{C}$; (c) Distribution of deformation in Z directions at $50\text{ }^{\circ}\text{C}$; (d) Distribution of deformation in X directions at $-15\text{ }^{\circ}\text{C}$; (e) Distribution of deformation in Y directions at $-15\text{ }^{\circ}\text{C}$; (f) Distribution of deformation in Z directions at $-15\text{ }^{\circ}\text{C}$.

The minimum strain for the simulated values was 1.11×10^{-5} in the Z direction in Figure 8c, and the minimum strain was 1.11×10^{-5} , while the maximum strain was over 5.06×10^{-5} . The measured value of the strain on the interior side was 9.79×10^{-6} and the strain at the board-to-mortar joint was 3.84×10^{-5} . The minimum strain of the simulated value of the Z direction deformation in Figure 8f was -1.15×10^{-5} on the interior side, and the maximum strain was close to -6.06×10^{-5} . The measured values were -9.86×10^{-6} for the interior side strain and -4.16×10^{-5} for the slab-to-mortar joint. The curve before 20 mm had the same trend as the analog value curve, showing an upward trend. Moreover, 20–35 mm between the measured value points of the connecting line showed a rising and then downward trend, which was close to the analog value curve in this interval of the basic changes in the trend. Specific values for critical locations at other temperature differences are shown in Table 6.

Table 6. Specific values for critical locations at other temperature differences.

Outdoor Temperature/ °C	Indoor Temperature/ °C	Value of Strain					
		X, Y Measured Maximum /10 ^{−5}	X, Y Measured Minimum /10 ^{−5}	Z Simulation Minimum /10 ^{−5}	Z Simulation Maximum /10 ^{−5}	Indoor Side Measured Value/10 ^{−6}	Board-to-Mortar Joint /10 ^{−5}
50	20	4.2	1.5	1.11	5.06	9.79	3.84
40	20	3.5	1.3	0.81	3.93	7.53	3.16
30	20	2.8	0.8	0.30	2.16	2.98	2.49
−15	20	−5.3	−1.6	1.15	−6.06	−9.86	−4.16
−10	20	−4.4	−1.4	−0.82	4.98	−9.11	−3.55
−5	20	−3.2	−1.0	−0.41	−3.72	−1.21	−2.58

4.3. Deformation Results of External Wall Thermal Insulation System Under Different Thicknesses

The EPS insulation board specimen along with the three thickness parameters of 30 mm, 50 mm, and 100 mm for the insulation board and 5 mm for the mortar were chosen. The two temperature conditions were established: an outdoor ambient temperature of 50 °C and a room temperature stabilization of 20 °C; an outdoor ambient temperature of −15 °C and a room temperature stabilization of 20 °C. The temperature deformation distribution of the insulation system consisting of 50 mm and 100 mm thickness EPS insulation boards, covered with 5 mm cement mortar, at an outdoor environment of 50 °C and a stable room temperature of 20 °C is shown in Figure 9. In Figure 9a,b, 0–50 mm was the thickness of the insulation board, and 50–55 mm was the thickness of the cement mortar; in Figure 9c,d, 0–100 mm was the thickness of the insulation board, and 100–105 mm was the thickness of the cement mortar.

From Figure 9a,b, in the 30 mm thick thermal insulation system when subjected to a temperature of 50 °C, the X and Y direction strain size increased gradually with the increase in the thickness of the thermal insulation system, and the thermal insulation system near the high-temperature side was more affected by the strain, which was greater than that of the indoor side. The side closer to the chamber had less strain relative to the heated side due to the smaller temperature change as well as constraint limitations. From Figure 9 it can be seen that the 50 mm and 100 mm insulation systems were close to the trend of the 30 mm insulation system when subjected to 50 °C temperature. The magnitude of the strain in the X and Y directions increased gradually with the thickness of the insulation system, and the strain was smaller on the side close to the interior under temperature change and confinement.

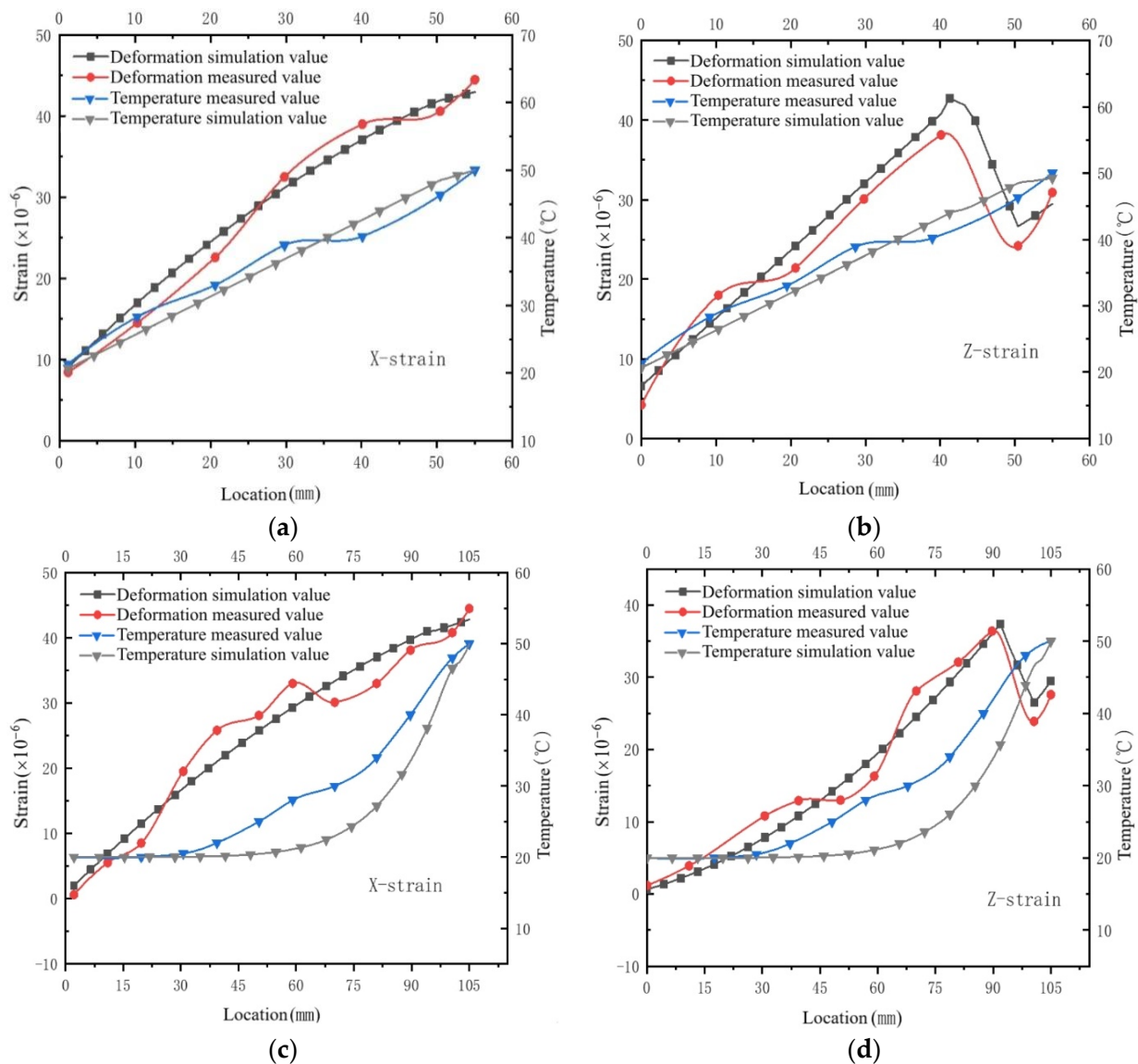


Figure 9. Temperature difference deformation distribution of insulation system along the board thickness in each direction for different board thickness insulation systems at 50 °C. (a) Distribution of deformation in X directions for 50 mm; (b) Distribution of deformation in Z directions for 50 mm; (c) Distribution of deformation in X directions for 100 mm; (d) Distribution of deformation in Z directions for 100 mm.

Under the outdoor ambient temperature conditions of 50 °C and −15 °C, when the thickness of the board was 30 mm, the maximum deformation of the insulation board was 0.0614 mm and 0.0719 mm; when the thickness of the board was 50 mm, the maximum deformation of the insulation board was 0.0615 mm and 0.0734 mm; when the thickness of the board was 100 mm, the maximum deformation of the insulation board was 0.0672 mm and 0.0779 mm. It can be seen that the greater the thickness of the insulation board, the greater the temperature deformation in the case of 50 °C and −15 °C because the overall thickness of the insulation system increased. According to Table 7, at two temperatures, 50 °C and −15 °C, the insulation board exhibited strain values in the X and Y directions that were not significantly affected by the board thickness. Three board thicknesses were close to each other in terms of strain at the same temperature; in the Z direction, as the thickness of the insulation board increased, its temperature deformation decreased. The strain of the insulation board was greatest at 30 mm of thickness, second biggest at 50 mm

of thickness, and smallest at 100 mm of thickness. At an outdoor ambient temperature of 50 °C, the width and length direction strain of the insulation board's indoor side decreased from 1.4×10^{-5} to 2.3×10^{-6} , or roughly 76% lower, and the thickness direction strain of the indoor side changed from 8.81×10^{-6} to 2.26×10^{-6} , or roughly 73% lower, when the thickness of the EPS board increased from 30 mm to 100 mm.

Table 7. Specific values for critical locations for different insulation board thicknesses.

Board Thickness /mm	Outdoor Temperature /°C	Value of Strain					
		X, Y Measured Maximum / 10^{-5}	X, Y Measured Minimum / 10^{-5}	Z Simulation Minimum / 10^{-5}	Z Simulation Maximum / 10^{-5}	Indoor Side Measured Value/ 10^{-6}	Board-to-Mortar Joint / 10^{-5}
30	50	4.2	1.5	1.11	5.06	9.79	3.84
50	50	4.4	0.9	0.61	4.45	5.81	2.52
100	50	4.4	0.2	≈ 0	3.72	2.26	2.38
30	−15	−5.3	−1.6	−1.15	−6.06	−8.81	-
50	−15	−5.2	−0.8	−0.82	−5.13	−9.11	-
100	−15	−5.2	−0.2	≈ 0	−4.06	≈ 0	-

4.4. Deformation Results of External Wall Insulation System Covering Different Thicknesses of Cement Mortar

Three different thermal insulation systems were constructed by selecting EPS insulation boards that were 30 mm thick and covering them with cement mortars that were 5 mm, 8 mm, or 10 mm thick respectively. The two temperature conditions were set: outdoor ambient temperature 50 °C, room temperature stabilized at 20 °C, and outdoor ambient temperature −15 °C, room temperature stabilized at 20 °C. The distribution of temperature deformation of the insulation system composed of 30 mm thickness EPS insulation board, covered with 8 mm and 10 mm cement mortar, in the outdoor environment of 50 °C and room temperature stabilization of 20 °C is shown in Figure 10. In Figure 10a,b, 0–30 mm was the thickness of the insulation board and 30–38 mm was the thickness of the cement mortar; in Figure 10c,d, 0–30 mm was the thickness of the insulation board and 30–40 mm was the thickness of the cement mortar.

The strain values at key positions under different mortar thicknesses are listed in Table 8. Under the outdoor ambient temperature conditions of 50 °C and −15 °C, the maximum deformation of the insulation board was 0.0614 mm and 0.0719 mm when covered with 5 mm mortar; 0.0635 mm and 0.0733 mm when covered with 8 mm mortar; 0.0732 mm and 0.0832 mm when covered with 10 mm mortar. It can be seen that the greater the thickness of the mortar, the greater the temperature deformation in the case of 50 °C and −15 °C because the overall thickness of the insulation system increased. The strain of each type of board decreased with increasing thickness of mortar cover under the action of two temperatures, 50 °C and −15 °C. At an outdoor ambient temperature of 50 °C, the width and length direction strains at the joint between the EPS insulation board and the mortar decreased from 3.9×10^{-5} to 3.4×10^{-5} , a decrease of approximately 12%, and the thickness direction strain on the interior side changed from 7.86×10^{-6} to 5.38×10^{-6} , a decrease of approximately 32% when the mortar thickness was increased from 5 mm to 10 mm.

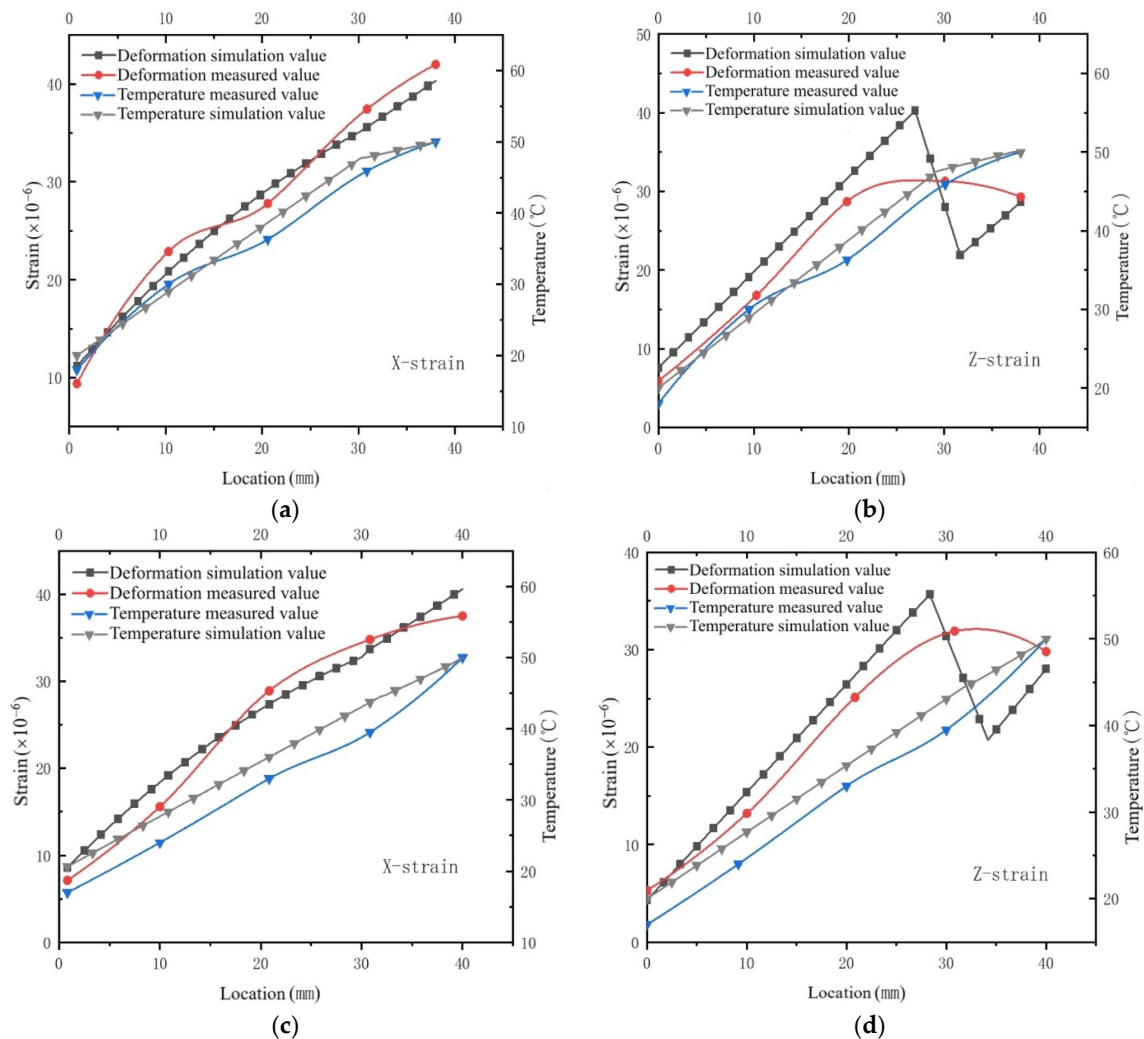


Figure 10. Temperature difference deformation distribution of insulation system along the board thickness in each direction for different mortar thickness insulation systems at 50 °C. (a) Distribution of deformation in X directions for 8 mm; (b) Distribution of deformation in Z directions for 8 mm; (c) Distribution of deformation in X directions for 10 mm; (d) Distribution of deformation in Z directions for 10 mm.

Table 8. Specific values for critical locations covered with varying thicknesses of cement mortar.

Thickness of Mortar /mm	Outdoor Temperature/ °C	Value of Strain					
		X, Y Measured Maximum /10 ^{−5}	X, Y Measured Minimum /10 ^{−5}	Z Simulation Minimum /10 ^{−5}	Z Simulation Maximum /10 ^{−5}	Indoor Side Measured Value/10 ^{−6}	Board-to-Mortar Joint /10 ^{−5}
5	50	4.2	1.5	1.11	5.06	9.79	3.84
8	50	3.9	0.9	0.86	4.16	6.56	3.26
10	50	3.9	0.6	0.53	3.53	5.38	3.06
5	15	−5.3	−1.7	−1.15	−6.06	−10.30	−
8	15	−4.5	−1.4	−0.51	4.93	−52.10	−
10	15	−4.7	−0.9	−0.50	−4.09	3.65	−

4.5. Deformation Results of External Wall Thermal Insulation System with Different Materials

Three different types of EPS, XPS, and PU insulation boards were chosen. The board thickness was 30 mm, and the mortar thickness was 5 mm. These two temperature con-

ditions were established: outdoor ambient temperature of 50 °C and room temperature stabilized at 20 °C; outdoor ambient temperature of −15 °C and room temperature stabilized at 20 °C. The distribution of temperature deformation of the insulation system composed of 30 mm thickness XPS and PU material insulation boards covered with 5 mm cement mortar in the outdoor environment of 50 °C and room temperature stabilization of 20 °C is shown in Figure 11. The thickness of the insulation board was 0–30 mm and 30–35 mm was the thickness of the cement mortar.

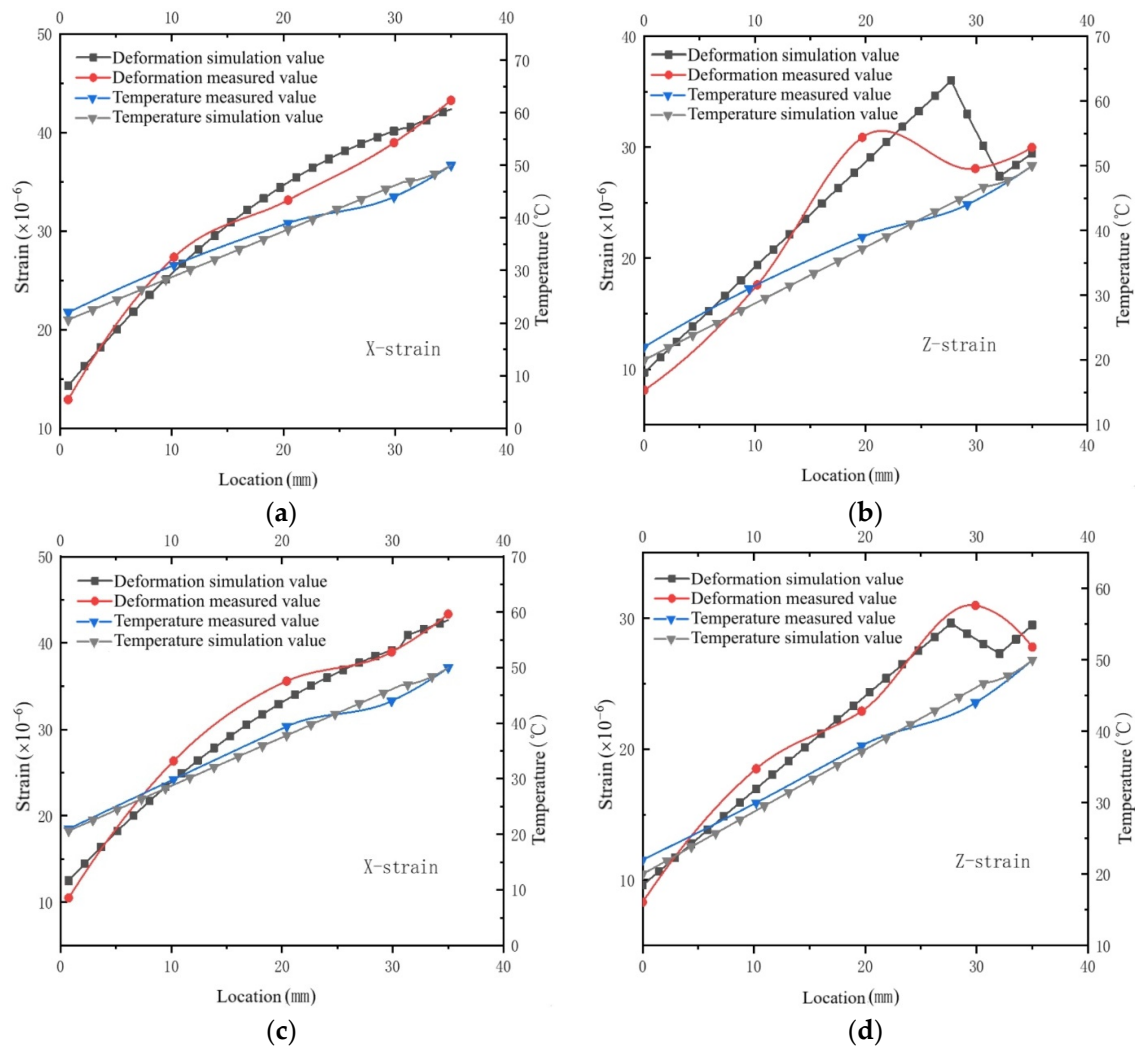


Figure 11. Temperature difference deformation distribution of insulation system along the board thickness in each direction at 50 °C for different materials of heat preservation system. (a) X direction deformation distribution of XPS insulation system; (b) Z direction deformation distribution of XPS insulation system; (c) X direction deformation distribution of PU insulation system; (d) Z direction deformation distribution of PU insulation system.

It should be noted that the values presented in Table 9 exhibit distinct directional dependencies; notably, the negative strain values in low-temperature scenarios correctly denote material contraction, with magnitudes accurately reflecting the scaling limits imposed by each board's thermal expansion coefficient.

Table 9. Key location-specific values for different materials.

Material of Insulation Board	Outdoor Temperature/ °C	Value of Strain				Indoor Side Measured Value/ 10^{-6}
		X, Y Measured Maximum / 10^{-5}	X, Y Measured Minimum / 10^{-5}	Z Simulation Minimum / 10^{-5}	Z Simulation Maximum / 10^{-5}	
EPS	50	4.2	1.5	1.11	5.06	9.79
XPS	50	4.1	1.4	1.00	3.72	8.12
PU	50	4.0	1.2	1.04	3.03	7.82
EPS	−15	−5.1	−1.6	−1.15	−6.08	−9.12
XPS	−15	−5.1	−1.4	−1.00	−4.06	−8.86
PU	−15	−5.1	−1.1	−1.13	−3.45	−8.13

Under the outdoor ambient temperature conditions of 50 °C and −15 °C, the maximum deformation of the EPS insulation board was 0.0614 mm and 0.0719 mm, the maximum deformation of the XPS insulation board was 0.0618 mm and 0.0722 mm, and the maximum deformation of PU insulation board was 0.0599 mm and 0.0708 mm. The strains in all boards decreased as the thickness of the mortar cover increased at two temperatures: 50 °C and −15 °C, as Table 9 illustrates. The three types of thermal insulation boards were closer to the X direction strain, while the Z direction strain varied more. This was because each material has different properties. The three types of insulation boards exhibited distinct temperature difference deformations, which can be attributed to variations in the insulation board's coefficient of linear expansion. The EPS board exhibited the highest strain among them, followed by the XPS board in second place and the PU board with the lowest.

4.6. Comparative Analysis of Experiment and Simulation

For an insulation system of the same material consisting of a 30 mm board thickness and a mortar thickness of 5 mm, the strain of each type of board increased with the temperature difference between the two sides of the board. Insulation board in the actual working condition of one side remains unchanged at room temperature, and on one side, by the outside world's high temperature or low temperature, deformation mainly occurs on the high-temperature or low-temperature side. At temperatures of 50 °C and −15 °C, the maximum strain of the insulation board along the board thickness in the X and Y directions was not much affected by the thickness of the board, and the rate of change in strain was affected by the board thickness. The temperature deformation decreased with increasing thickness of the insulation board; insulation board strain along the board thickness decreased with increasing thickness of the covering mortar.

Although the difference in linear expansion coefficient mainly leads to thermal deformation, the actual interfacial strain is closely related to the elastic modulus and Poisson's ratio of the constituent materials. For example, a higher modulus of elasticity in cement mortar limits the free expansion of softer insulation panels, converting the free thermal expansion into constrained internal stresses. Furthermore, different thermal conductivities determine the internal temperature gradient; the lower thermal conductivity of polyurethane sheets causes a steeper drop in temperature, which changes the strain distribution in the thickness direction. It is important to emphasize that the calculated maximum interfacial strain values (e.g., reaching up to 4.2×10^{-5} or 42 $\mu\epsilon$) approach the lower limit of the typical tensile cracking strain threshold for standard cement mortars (approximately 100 to 150 $\mu\epsilon$). Therefore, the accumulation of these thermal strains under extreme or prolonged temperature gradients makes it highly likely that microcracks and subsequent interfacial debonding will occur.

The curves connected with the measured values and the numerical simulation curves in Figures 8–11 did not exactly coincide with each other due to the slight difference between

the experimental material properties and the numerical simulation setup values, but the overall trend was the same (falling within the 15% error margin). The insulation system's internal temperature distribution exhibited a nearly linear distribution, with the central portion of the match being lower than the ends and the measured temperature curve at both ends being closer to the calculated value curve. In the deformation numerical simulation, it was assumed that the materials in each structural layer of the heat preservation system were homogeneous and would not be damaged during the simulation process, and the connections between the heat preservation board and the interface mortar, and between the heat preservation board and the cement mortar of the surface layer were set up to be completely fixed and would not be sliding relative to each other, whereas the bonding of the different materials under the real condition will not be completely adhered to, and thus will be moving relative to each other.

In the numerical simulation analysis, the temperature on both sides of the insulation board was set to a fixed value for ideal experimental conditions, and the temperature control device would have some errors during the test. There would be some mistakes because these presumptions differ from the actual testing procedure. The thermal conductivity of the insulation board would change with the moisture content, and the thermal conductivity would be larger when the moisture content was larger. During the low-temperature deformation test, refrigeration on one side of the insulation board caused water vapor to condense on the surface of the board, and the thermal conductivity of the board changed accordingly. During the high-temperature deformation test, the insulation board would soften with the increase in temperature and the modulus of elasticity would decrease. Thermal conductivity, specific heat capacity, thermal expansion coefficient, and other thermodynamic parameters were the main factors affecting the good or bad deformation in the numerical simulation process. The physical parameters of insulation boards of different material origins and material batches had large dispersion, and the materials used in the test would have certain errors with the specification values of the materials used in the simulation, which would lead to different data between the simulation results and the test results. There was a discrepancy between the simulation curve and the measured curve because of the necessity to cut the insulation board to place the thermocouples inside; in some cases, this would destroy the continuity of the insulation board and affect temperature conduction.

5. Conclusions

The deformation rule and stress distribution of the external wall insulation system with various materials, thicknesses of external wall insulation materials, and covering thicknesses of mortar under various temperature difference conditions were analyzed in this paper using numerical simulation and experimental research methods. The main conclusions are as follows:

(1) According to the simulation analysis, the internal temperature stress distribution in the constrained state around the insulation system was roughly stepped. Surface cement mortar experienced compressive stress at high temperatures; the wall of the thermal insulation system experienced compressive stress at low temperatures, and surface cement mortar experienced greater tensile stress.

(2) For an insulation system of the same material consisting of a 30 mm board thickness and a mortar thickness of 5 mm, the strain of the various boards increased with the temperature difference between the two sides of the board. At high temperatures of 50 °C, 40 °C and 30 °C working conditions, when the temperature difference increased from 10 °C to 30 °C, the width and length direction strains at the joint of the EPS board and mortar changed from 2.8×10^{-5} to 4.2×10^{-5} , which increased by about 32%, and the maximum

strain in the thickness direction increased from 2.49×10^{-5} to 3.84×10^{-5} , which increased by about 35%.

(3) Under the influence of 50 °C and −15 °C, the maximum strain of the insulation board along the board thickness X and Y directions was not affected by the board thickness, and the strain change rate was affected. When the thickness of the EPS board was increased from 30 mm to 100 mm, the width and length direction strains on the interior side of the insulation board were reduced from 1.4×10^{-5} to 2.3×10^{-6} , a reduction of about 76%, and the thickness direction strain on the interior side was changed from 8.81×10^{-6} to 2.26×10^{-6} , a reduction of about 73%.

(4) The strains in all boards decreased as the thickness of the mortar cover increased at two temperatures: 50 °C and −15 °C. When the mortar thickness was increased from 5 mm to 10 mm, the width and length direction strains at the joint between the EPS insulation board and the mortar were reduced from 3.9×10^{-5} to 3.4×10^{-5} , a reduction of about 12%, and the thickness direction strain on the interior side was changed from 7.86×10^{-6} to 5.38×10^{-6} , a reduction of about 32%.

(5) Each material within the insulation system had a different magnitude of temperature difference deformation due to the different properties of each material, and the three types of insulation boards had a close strain in the X direction and a larger strain gap in the Z direction. There exist different thermal insulation systems due to the varying linear expansion coefficients of the insulation board, and the three kinds of insulation boards also exhibited distinct thermal deformations due to temperature differences. Among them, the EPS board has the largest strain, the XPS board has the second largest strain, and the PU board the smallest.

(6) The numerical model developed in this study relies on ideal elastic boundary assumptions (e.g., complete bonding). While it successfully captures the peak theoretical interfacial strains prior to failure, future models should incorporate non-linear cohesive zone elements to directly simulate debonding and crack propagation.

Author Contributions: Conceptualization, L.L. and J.L. (Jiayou Liu); methodology, L.L.; software, L.L.; validation, L.L., S.L. and J.S.; formal analysis, X.L.; writing—original draft preparation, L.L.; writing—review and editing, J.S.; visualization, J.L. (Jingyang Li); funding acquisition, J.L. (Jiayou Liu). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Taian Science and Technology Innovation Development Program, grant number 2022GX083.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Xin Li is employed by the Shanghai Urban Construction Municipal Operation (Group) Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EPS	Expanded Polystyrene
XPS	Extruded Polystyrene boards
MW	Mineral wool
ETICS	External thermal insulation composite systems
ITPS	Integrated thermal protection system
GHB	Glazed Hollow Beads
IDBs	Insulation decorative boards

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