Experimental study on temperature variations of prefabricated sandwich insulated facade panels using truss-type connectors

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Abstract. Full-scale temperature tests were conducted on inner and outer wythes with single-piece truss connectors, both with and without openings, connected to sandwich insulation wall panels. The purpose of the study was to investigate the deformation and stress performance of these panels under temperature differentials between the inner and outer wythes. The test results showed that throughout the temperature variation process, the concrete temperature of the inner wythe remained stable. The sandwich insulation layer exhibited good thermal insulation performance, and the heat transfer through the connectors had minimal impact on the temperature changes of the inner wythe. During the cooling process, no cracks were observed on the surface of the specimens. During the heating process, the crack widths of both specimens remained below 0.2mm. The overall effect of temperature on the outer wythe, constrained by the inner wythe, was relatively small. Under the influence of temperature difference, the specimens exhibited some warping deformation. However, the deformation values did not exceed the allowable limits for the facade panels.

Keywords: Prefabricated; Facade panels; Temperature test; Connections for insulation wall.

1 Introduction

With the increasingly severe global energy shortage and environmental pollution issues, the construction industry, being a major consumer of energy and emitter of carbon, needs to take effective measures to reduce energy consumption and carbon emissions [1,2]. Prefabricated ultra-low energy buildings offer advantages such as improved energy efficiency, reduced carbon emissions, enhanced residential comfort, and minimized environmental pollution, making them an important direction for future green building development. Among them, prefabricated ultra-low energy sandwich insulated facade panels, as a crucial component of prefabricated ultra-low energy buildings, can

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effectively reduce carbon emissions and improve energy conversion rates [3,4]. Therefore, research on temperature tests of prefabricated ultra-low energy sandwich insulated facade panels holds significant importance in promoting the development of green buildings.

The construction of sandwich insulated concrete facade panels is a common form in prefabricated building facades. These panels are composed of two layers of reinforced concrete with insulation material filled in between, forming a composite panel[5,6]. The connection between the inner and outer wythes and the intermediate insulation board is achieved through specialized connectors, forming a unified structure. Based on the configuration and quantity of connectors, sandwich insulated panels can be classified as fully composite panels, non-composite panels, or partially composite panels [7]. For sandwich insulated shear walls, the current design approach in China generally adopts the non-composite design concept, aiming to achieve minimal constraints on the outer wythe from the inner wythe, thereby allowing free deformations under temperature effects. The use of truss-type connectors in sandwich insulated shear walls may lead to significant constraints on the deformation of the outer wythe by the inner wythe under temperature effects. This combination effect between the inner and outer wythes increases the risk of bending deformations and cracking of the outer wythe under temperature differentials between the inner and outer wythes. Additionally, the thermal conductivity of the connectors is much higher than that of the inner and outer wythes and insulation layer, resulting in thermal bridging effects and potential cracking risks in the concrete near the connectors [8,9]. Therefore, it is necessary to study the performance of sandwich insulated shear walls using this type of connector under temperature effects.

This study investigates the deformation capacity and cracking patterns of the outer wythe of sandwich insulated wall panels, both with and without openings, under temperature differences between the inner and outer wythes. The panels were subjected to both heating and cooling processes.

2 Test program

2.1 Specimen design

The dimensions of the specimens and the arrangement of connectors were determined based on commonly used thermal insulation facade panels in actual engineering. Two full-scale specimens were designed: one without openings (specimen WQ-1) and one with an opening (specimen WQ-2). The inner wythe of the specimens has a thickness of 200mm, the outer wythe has a thickness of 60mm, and the insulation layer has a thickness of 270mm. The width of the specimens is approximately 3m, and the height is around 2.7m. For the specimen with an opening, the opening is centered in the width direction, with a distance of 0.9m from the bottom of the wall, and the size of the opening is 1.4m × 1.4m. Detailed dimensions of the specimens and the arrangement of connectors can be seen in Figure 1. The concrete strength grade of the specimens is C30.

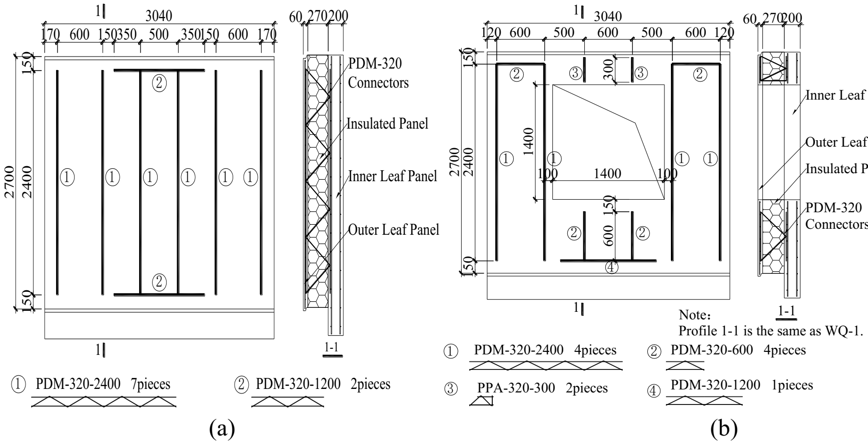


Fig. 1. The specimen dimensions and arrangement of connectors.

The connectors used for the inner and outer wythes are PDM320 single-piece truss-type connectors manufactured by Peck. The total height of the connector is 320mm, with 25mm embedded into the concrete on each side. The length and spacing of the connectors are designed and arranged by the manufacturer. The construction and dimensions of the connectors can be seen in Figure 2.

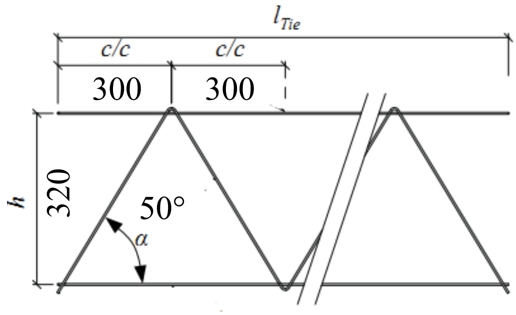


Fig. 2. The construction and dimensions of the connectors.

2.2 Test equipment

A homemade temperature control chamber was used for the temperature tests. The experimental setup is shown in Figure 3. A temperature control chamber was installed on one side of the outer wythe. Inside the temperature control chamber, refrigeration and heating equipment were set up for cooling and heating purposes. The wall panels were placed at the junction of the indoor and outdoor openings. The gap between the opening and the wall panel was filled with polyurethane foam to ensure a tight seal and prevent heat loss. The temperature variations were controlled indoors. For cooling, refrigeration air conditioners were used, and the air temperature could reach -25℃. For heating, ceramic heating elements were installed in the air conditioner, supplemented by infrared heating lamps. The heating lamps were arranged in 3 rows and 3 columns, a total of 9 lamps, evenly distributed along the height.

2.3 Temperature application program

Referring to European standard EN1991-1-5[10] and American standard ASTM C1472[11], the temperature requirements for the facade surface are specified. Considering the worst-case scenario (dim southwest wall), the maximum temperature and minimum air temperature of the outer surface of the wall panel are determined as follows: For summer, the maximum outer wythe surface temperature is set as the basic temperature (T_{max}) plus 42°C. For winter, the minimum outer wythe surface temperature is set as the basic temperature (T_{min}). The wall panel surface temperatures can be found in Table 1.

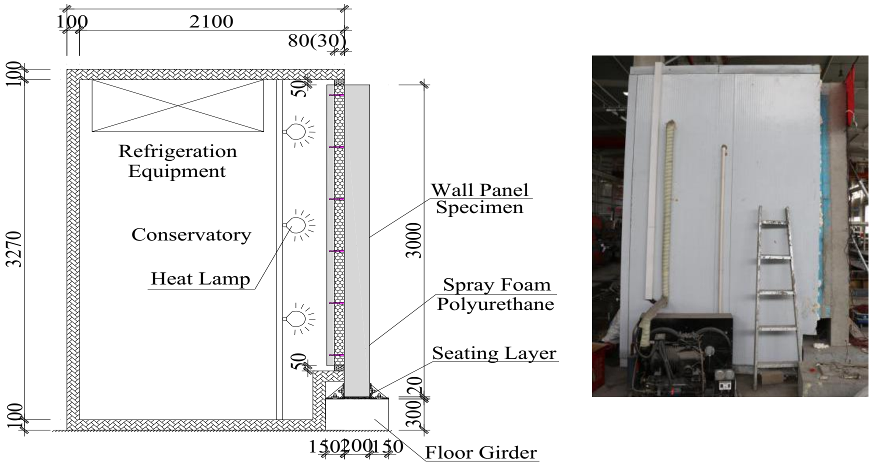
Table 1. Surface temperature of the facade and indoor-outdoor temperature difference.

Season	Base temperature(°C)	Indoor temperature(°C)	Surface temperature of facades(°C)	Temperature difference(°C)
Summer	38	25	80	65
Winter	-15	25	-25	50

During the experiment, the temperature is first lowered and then raised. Once the target temperature is reached, it is maintained for approximately 3 hours before the temperature application is stopped. After that, observations and recordings of the experimental phenomena are conducted indoors.

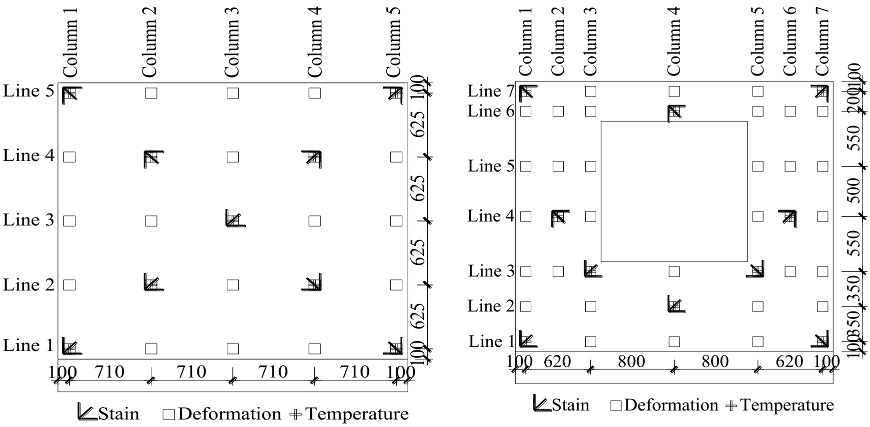
2.4 The arrangement of measurement points

Measurements include controlling temperature inside and outside the control room, concrete temperature in the inner and outer wythes, concrete strain in the inner and outer wythes, out-of-plane deformation of the outer wythe, and resulting cracks. Temperature sensors are used to display and collect indoor and outdoor temperatures. Resistance temperature sensors and three-axis strain gauges are strategically placed at typical locations on the specimens. After the heating and cooling processes, measurements are taken inside the control room to determine the out-of-plane deformation, crack distribution, and crack width of the outer wythe.The layout of temperature, strain, and deformation measurement points can be seen in Figure 4. The inner and outer wythes temperature sensors are numbered as NT_{ij} (representing the temperature of the i-th row and j-th column measurement point) and WT_{ij}, respectively. Strain measurement points are denoted as S_{ij}, while deformation measurement points are labeled as D_{ij}.



(a) (b)

Fig. 3. Test equipment.

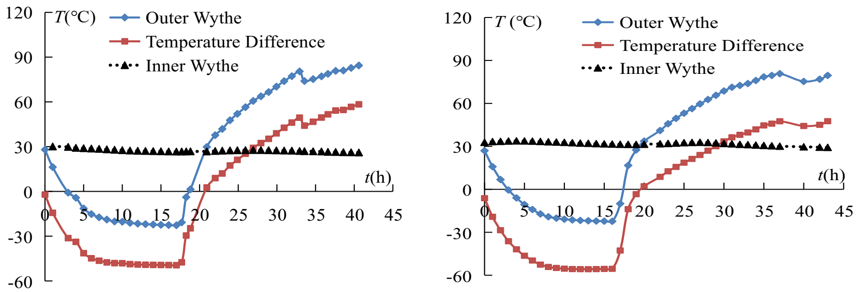


(a) (b)

Fig. 4. The arrangement of measurement points.

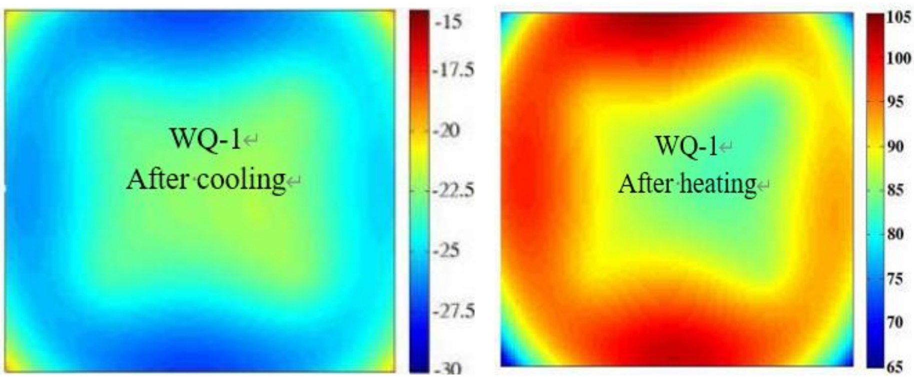
3 Experimental procedure

The temperature distribution of the concrete in the inner and outer wythes of the specimens, as well as the relationship between temperature difference and time during the cooling and heating processes, are shown in Figure 5 and Figure 6. From the figures, we can observe the following: During the cooling process, the temperature of the outer wythe decreases rapidly initially. As the temperature reaches a certain level, the rate of temperature reduction gradually slows down, and the temperature stabilizes. During the heating process, the temperature of the outer wythe increases approximately linearly with time. Once the temperature reaches a certain level, the rate of temperature increase starts to slow down. The temperature of the inner wythe remains stable throughout the cooling and heating processes, indicating that the insulation performance of the sandwich insulated wall panel is good and the heat transfer through the connectors has minimal impact on the temperature of the inner wythe. For specimen WQ1, after the cooling process, the temperature along the perimeter is lower than the internal temperature.. The maximum and minimum values of the measured temperatures differ by only 1.9°C, indicating a relatively uniform temperature distribution. However, after the heating process, the temperature along the perimeter is higher than the internal temperature. The maximum and minimum values of the measurement points differ by 13.2°C, indicating a less uniform distribution. For WQ2, the temperature values at the top two corner areas of the opening and the bottom area of the specimen are higher than the rest. During the cooling process, the difference between the maximum and minimum values of the measurement points is 7.3°C, while during the heating process, the difference is 15.4°C.

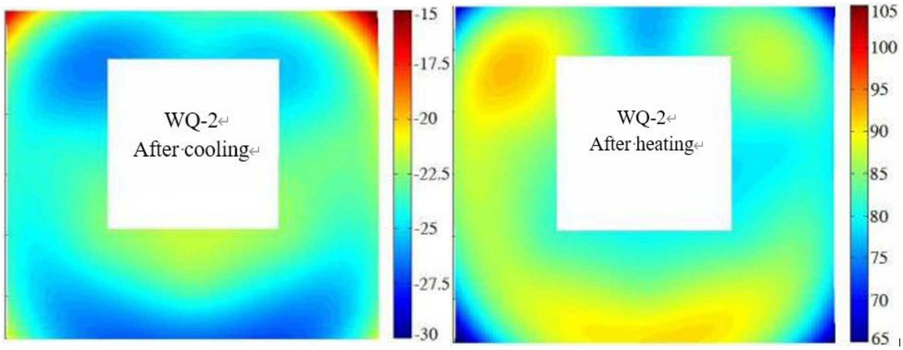


(a) (b)

Fig. 5. Temperature and temperature difference variation curves of the concrete in the inner and outer wythes.



(a) (b)



(c) (d)

Fig. 6. Temperature contour map of the outer wythe after cooling and heating processes.

4 Analysis of results

4.1 Crack analysis

Specimen WQ-1. Both specimens showed no cracks in the inner wythe after the cooling and heating processes. According to the connector configuration and form described in this article, the thermal bridging effect created by the connectors is not sufficient to cause cracking in the concrete near the inner wythe.

Specimen WQ-1 did not exhibit any surface cracks on the outer wythe after the cooling process. However, multiple cracks appeared on the surface of the outer wythe after the heating process, as shown in Figure 7. From the figure, we can observe two main types of cracks on the inner surface of the outer wythe: short diagonal cracks and long cracks. The short diagonal cracks occur due to thermal expansion and deformation of the outer wythe during heating, coupled with surface cracking caused by rapid water loss from the concrete. The long cracks mainly originate from and extend along the shorter cracks, intersecting and forming longer cracks. Several vertical cracks perpendicular to the lower edges and bottom edges of the outer wythe are also observed, some of which extend inward and nearly connect with the longer internal cracks. This is mainly attributed to the uneven temperature and strain distribution near the specimen's edges, as well as the constraints imposed by the connectors located near the edges. Overall, although there are several surface cracks on the outer wythe, their widths are relatively small, with none exceeding 0.2mm. Additionally, it is important to consider that in actual engineering applications, the outer wythe surface is usually covered with finishing materials, providing some level of crack resistance and waterproofing. Therefore, it can be concluded that the specimen meets the functional requirements for normal usage.

Specimen WQ-2. Specimen WQ-2 exhibited surface cracks only on the outer wythe after the heating process, similar to specimen WQ-1. The distribution of these cracks is shown in Figure 8. From the figure, we can observe that there are only a few cracks present at the edges of the opening in the outer wythe. This is because the presence of the opening reduces the constraints on the specimen itself, thereby reducing the internal forces generated due to temperature changes and resulting in fewer cracks. The cracks at the left edge of the opening develop horizontally, while the cracks at the lower edge of the window develop vertically. All of the cracks observed are short cracks. The formation of these cracks is attributed to the thermal expansion and deformation of the outer wythe during heating, uneven deformation at the edge of the window, and localized constraints. However, all crack widths are within 0.05mm. Overall, it can be concluded that the specimen meets the functional requirements for normal usage, as the number of cracks is minimal and their widths are small.

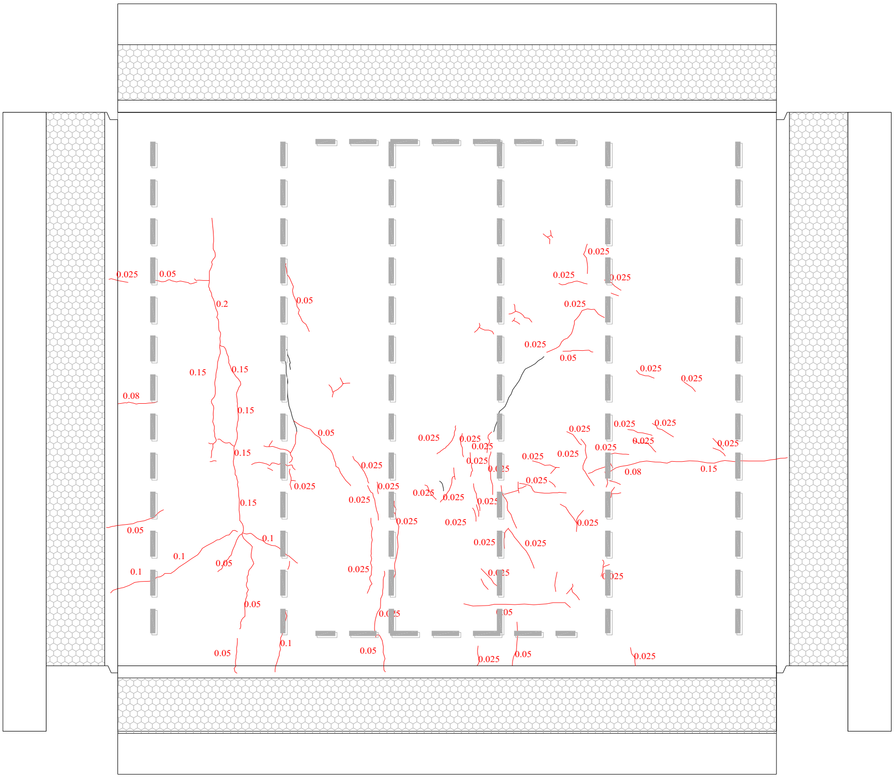


Fig. 7. Cracks on the surface of the outer wythe after heating of WQ-1.

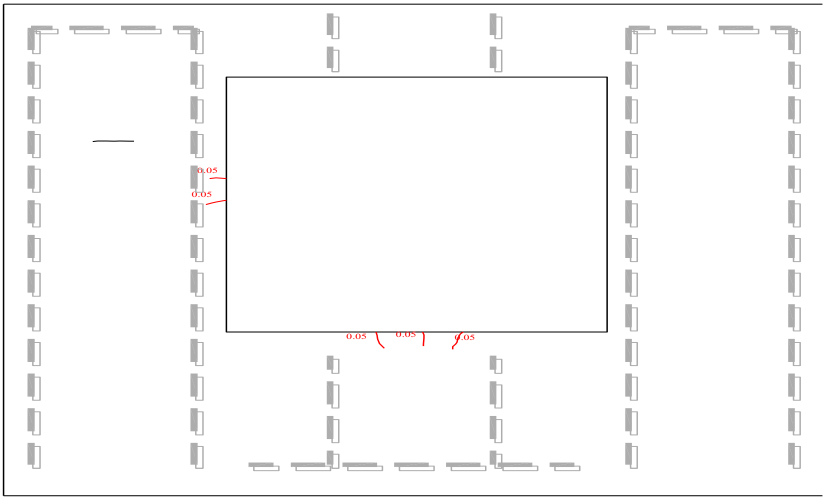


Fig. 8. Cracks on the surface of the outer wythe after heating of WQ-2.

4.2 Concrete Strain Analysis

The strain variation curves of typical measurement points in the outer wythe concrete for specimens WQ-1 and WQ-2 with respect to temperature difference are shown in Figure 9 and Figure 10. In the figures, H represents horizontal strain, V represents vertical strain, X represents diagonal strain at 45 degrees, Max represents maximum principal strain. The strains are calculated according to equations (1) - (2), where the theoretical strains are based on the assumption of free expansion and contraction of the outer wythe. Calculation is performed using equation (3).

$$\gamma_{xy} = 2\varepsilon_{X} - (\varepsilon_{H} + \varepsilon_{V}) \tag{1}$$

$$\varepsilon_{Max} = \frac{\varepsilon_{H} + \varepsilon_{V}}{2} + \sqrt{(\frac{\varepsilon_{H} - \varepsilon_{V}}{2})^2 + \gamma_{xy}^2} \tag{2}$$

$$\varepsilon_{t} = \alpha\left[(T_{wi} - T_{w0}) - (T_{ai} - T_{a0})\right] \tag{3}$$

In the equations, ε_H, ε_V, and ε_X represent vertical, horizontal, and diagonal strains, respectively. ε_{Max} represents the maximum principal strain. γ_{xy} represents the shear stress in the direction of study. α represents the coefficient of linear expansion, which is taken as 1×10^{-5}/°C for concrete. T_{wi} and T_{ai} represent the temperature of the outer wythe of concrete and the outdoor control room at the i-th hour, respectively. T_{w0} and T_{a0} represent the initial temperature of the outer wythe of concrete and the outdoor control room at the start of the experiment, respectively.

From Figure 9 and Figure 10, the following observations can be made:

(1)For specimen WQ-1, both during cooling and heating, the measured strain values show a linear relationship with temperature difference. The calculated theoretical strains based on free expansion and contraction also agree well with the measured strains.

(2)For specimen WQ-2, during the cooling process, the measured strain values at each measurement point exhibit a linear relationship with temperature difference. However, during the heating process, the measured strain curve continues to increase rapidly after the temperature difference reaches zero, followed by a rapid flattening of the curve. This is mainly due to the presence of an opening in WQ-2, which allows heat to affect the side surface of the opening. As a result, the local temperature on the outer wythe surface becomes excessively high. Moreover, since the outer wythe is less constrained by the inner wythe in that area, it exhibits significant deformation. These factors together contribute to a rapid increase in strain, causing the measured strain to be much larger than the theoretical strain.

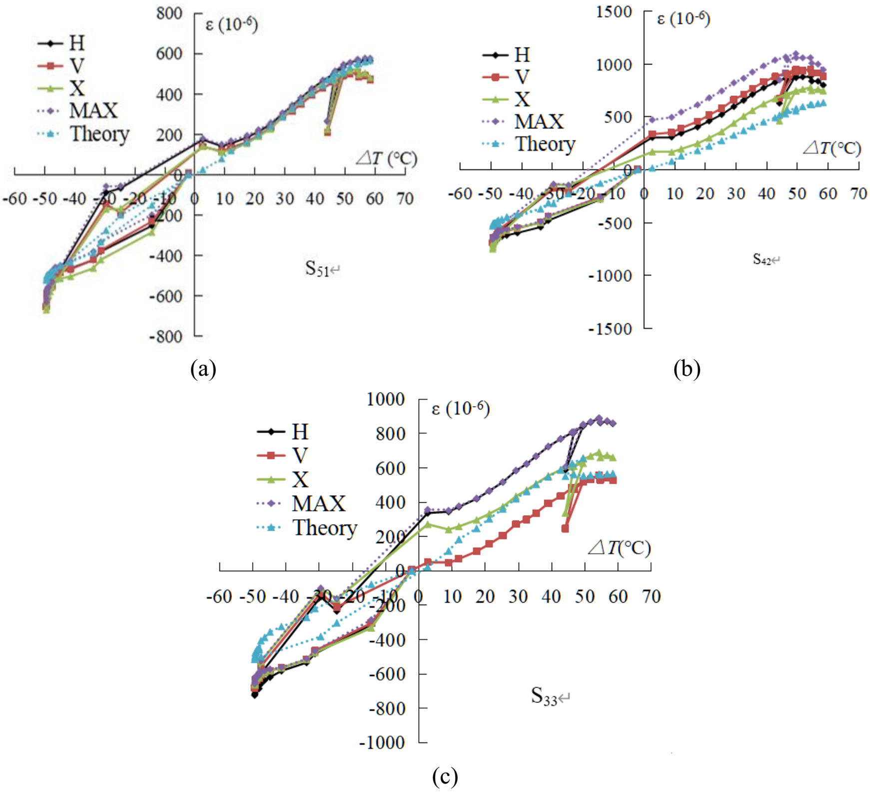


Fig. 9. Strain variation curve of the outer wythe concrete in WQ-1 with respect to temperature difference.

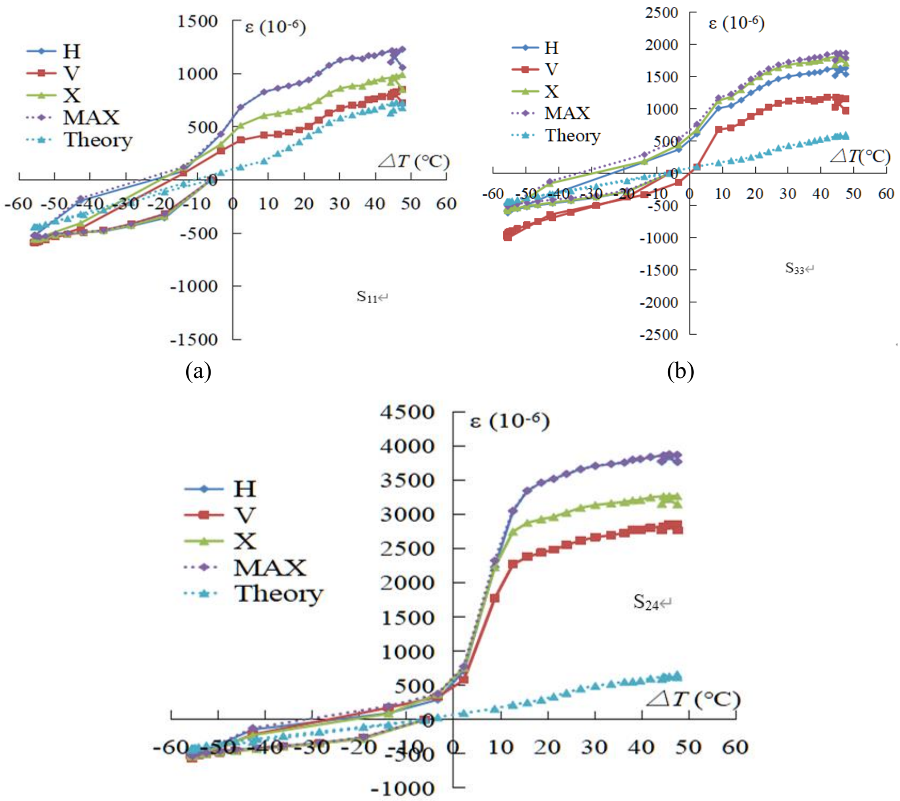


Fig. 10. Strain variation curve of the outer wythe concrete in WQ-2 with respect to temperature difference.

4.3 Analysis of out-of-plane deformation

The measured out-of-plane deformation distribution of specimens WQ-1 and WQ-2 is shown in Figure 11, and the statistics of the maximum out-of-plane deformation on the outer wythe are presented in Table 2. From these results, the following observations can be made:

(1)For specimen WQ-1, under temperature effects, primarily overall and continuous warping deformation occurs. During cooling, the out-of-plane deformation is relatively small near the edges, while the central concave portion experiences larger deformations. During heating, the edge deformations are smaller, while the central region shows significant outward convex deformations.For specimen WQ-2, due to the presence of a window opening, localized warping deformation mainly occurs under temperature effects. During cooling, noticeable inward concave deformations occur at the lower edges on both sides, the top edge of the window opening, and the corner of the opening. Other areas mainly experience outward convex deformations.

(2)The maximum deformation observed in WQ-1 during the test process is approximately 6mm in either rows or columns. In contrast, WQ-2 exhibits a maximum deformation of approximately 3.5mm.

The ratio of the maximum deformation to the short side length of the outer wythe in specimens WQ-1 and WQ-2 is 1/450 and 1/771, respectively. According to the reference standard *Technical standard for* application *of precast concrete facade panels* (JGJ/T 458-2018) [12], it stipulates that the allowable limit for out-of-plane deflection of curtain wall panels is 1/250 of the distance between the outer supports.Based on this requirement, it can be observed that the maximum deformation of the outer wythe under temperature effects is significantly smaller than the specified limit, indicating compliance with the requirements.

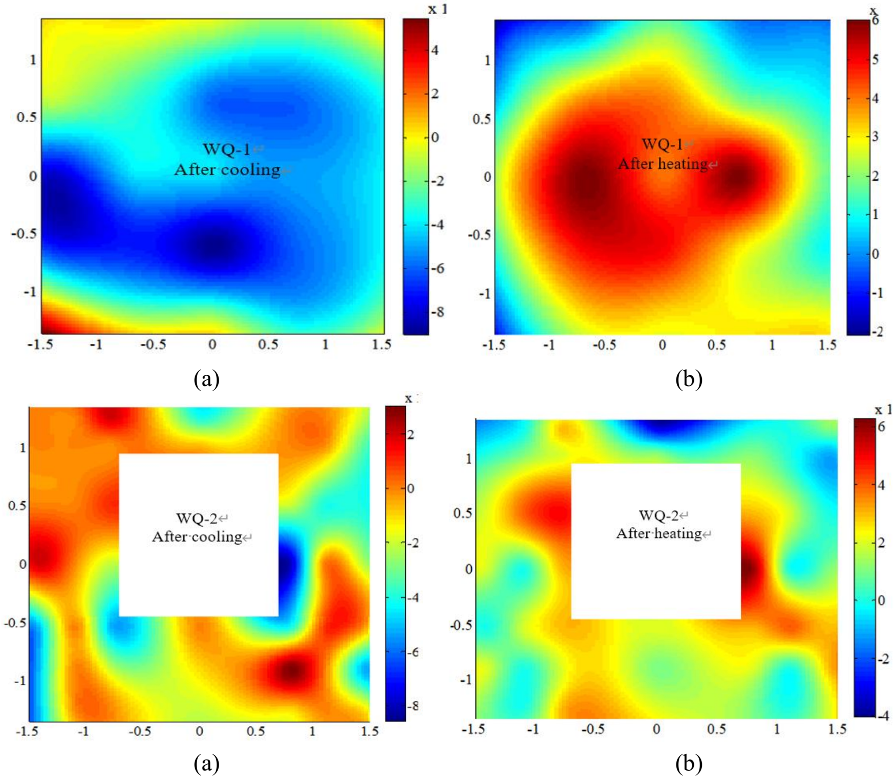


Fig. 11. Out-of-plane deformation contour maps of the outer wythe after cooling and heating.

Table 2. Maximum out-of-plane deformation of the outer wythe.

Specimen number	Deformation after cooling (mm)	Deformation after heating (mm)
WQ-1	By line: average 3.25	By line: average 2.85
	By column: average 5.90	By column: average 3.50
WQ-2	By line: average 3.55	By line: average 2.85
	By column: average 3.45	By column: average 2.70

5 Conclusion

Two specimens with truss connectors for sandwich insulation facade panels were subjected to performance tests under temperature effects. During the test process, measurements were taken for temperature, strain, cracks, and deformations. Based on this study, the following conclusions can be drawn:

(1) Both cooling and heating of the outer wythe of concrete exhibit a pattern of initially rapid, followed by slower changes. During cooling, the outer wythe of concrete shows relatively uniform behavior, while during heating, the temperatures are higher around the opening and the outer edges.

(2) The temperature of the inner wythe concrete remains stable throughout the temperature variations, with no cracks observed. The insulation boards provide effective thermal insulation, and the thermal bridging effect caused by the connectors has minimal impact on the inner wythe. Overall, the mutual constraints between the inner and outer wythes are relatively small under temperature effects.

(3) Neither of the two specimens exhibited cracks in the outer wythe after cooling, while after heating, the specimen without an opening experienced several internal cracks, each with a width not exceeding 0.2mm. The specimen with an opening had a few short and thin cracks along the edge of the window opening, with a crack width not exceeding 0.05mm. Overall, the facade panels in this test meet the functional requirements for normal use.

(4) In the specimen without an opening, the measured strain values of the outer wythe of concrete show a linear relationship with temperature difference. The theoretical strains calculated based on free expansion and contraction agree well with the measured strains during the cooling phase. However, in the specimen with an opening, due to less constraint and localized high temperature, the measured strains at the opening location are larger than the theoretically calculated strains.

(5) In the specimen without an opening, the outer wythe primarily undergoes overall and continuous warping deformation under temperature effects. During cooling, significant inward concave deformations occur in the central part of the wall panel, while noticeable outward convex deformations occur in the central part during heating. In the specimen with a window opening, localized warping deformation mainly occurs under temperature effects. During cooling, noticeable inward concave deformations occur at the lower edges on both sides, the top edge of the window opening, and the corner of the opening. Other areas mainly experience outward convex deformations. The maximum bending and torsional deflections of the two specimens after cooling are approximately 6mm, while the maximum out-of-plane deformation after heating is about 3.5mm, which satisfies the limits specified in the standards.

Acknowledgments

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References

1. Wu Q, Tu K, Zeng Y F (2023) Reflections on China's energy strategy situation under the vision of "dual-carbon" goal. Chinese Science Bulletin., 15: 1884-1898.
2. Song X J, Zhai S F, Wang Y Y (2023) Research on Countermeasures for Low-Carbon Development of the Whole Life Cycle of Construction Engineering under the Goal of "Double Carbon". Construction Economy., 03: 11-17.
3. Wu Z M, Chu H L, Yin S W, et al. (2021) Research on thermal bridge control measures of prefabricated sandwich insulation wall panels for assembled ultra-low energy buildings. Construction Technology., 03: 79-81.
4. Wang J, Zhang S B, Li R X, Yang M (2018) Analysis of the development status and application of assembled ultra-low-energy buildings. Construction Wall Innovation & Building Energy-Saving., 06: 33-36.
5. O'Hegarty R, Kinnane O (2020) Review of precast concrete sandwich panels and their innovations. Construction and Building Materials., 233: 117-145.
6. Xiao X, Yang Y, Zhou Y, et al. (2021) Research progress of assembled concrete facade panels. Create Living., 01: 08-10
7. Yang J L, Xue W C (2012) Progress in the Application of FRP Connectors for Prefabricated Sandwich Insulated Walls. Low Temperature Architecture Technology., 08: 139-142.
8. Chen D G, Yao Y, Wang H J, et al. (2014) Experimental study on thermal insulation structure of foam concrete insulation panel. Concrete., 06: 133-136.
9. Zhang J Y, Lu G Z, Guo Z L, et al. (2020) Research on Thermal Performance of Precast Sandwich Concrete Wall Panels. China Concrete and Cement Products., 10: 69-71.
10. EN 1991-1-5 (2010) Eurocode 1: actions on structures:part1-5: general actions-thermal actions. British Standards Institution, England.
11. ASTM C1472 (2010) Standard guide for calculating movement and other effects when establishing sealant joint width. American Society of Testing Materials, New York.
12. JGJ/T 458 (2018) Technical standard for application of precast concrete facade panels. China Architecture & Building Press, Beijing.