THE COUPLING EFFECT FROM THE ACTION OF MULTIPLE FACTORS ON THE COMPOSITE WALL WITH OUTER LIGHTWEIGHT INSULATING LAYER

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ABSTRACT

The reason why covering plaster layers in lightweight insulating composite wall are easily to be damaged is related with many factors. In this paper, the coupling effect of multiple factors such as temperature, wind, gravity, different physical and mechanical properties of constructional materials, is assumed to be the cause. A set of special device is designed to simulate and test the coupling effect. And the test specimens based on practical project are classified into two groups in given conditions. The distribution of temperature and the characteristic curves of coupling stress and strain of different layers in different conditions have been sorted out based on the data from the test and theoretical analysis with FEM tools. The results show that the peak stress and strain at some parts in covering layers is larger under the impact of multiple factors than that of a single factor. The peak stress and strain at covering layers in the coupling situation is amplified up to75% compared with that under temperature effect.

Keywords: *Lightweight Thermal Insulating System, Coupling Effect, Damaged Mechanism, Constraint between Materials.*

1. INTRODUCTION

Since the 1980s, dozens of outer lightweight insulating systems have been developed in China. And some insulating systems have been used in buildings to meet the demand of energy conservation. However, the plaster covering layers were damaged in many external walls with outer lightweight insulating system (as shown in Fig.1). This kind of damage brings many problems such as reducing the energy-saving efficiency, increasing the risk of causing personal injury or property loss and defacing the building [1].

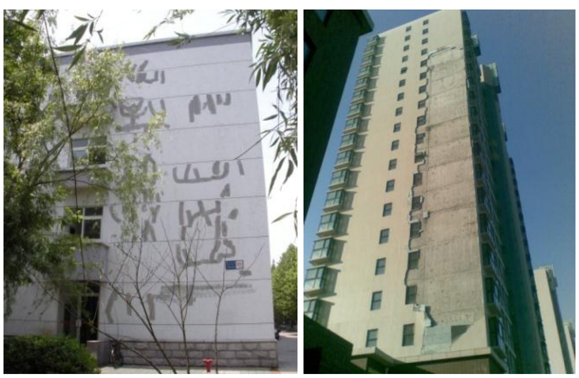


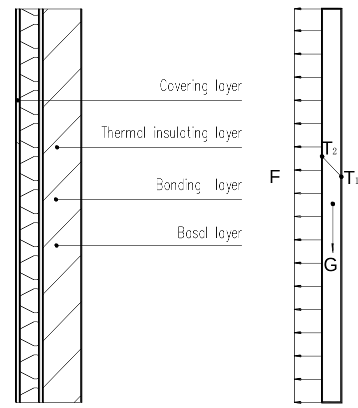
Fig.1 Damage of the covering plaster layer

In order to find out the reason why the covering plaster layers of outer lightweight composite insulating wall are easily to be damaged, many works have been conducted with the consumption of the conflict of material functions, high temperature stress, and so on. Zhenli Huang, Gang Liu, et al. analyzed and tested the temperature stress and weather-ability in outer lightweight insulating system, and put forward corresponding design specification of structure and material parameters based on their large-scale weather-ability test with different construction and materials[2]-[4]. Bernhard Polt proposed an analysis method of thermal stress in outer insulating system.[5] Xin Wang and Yonghua Lu presented a distribution characteristic of stress and strain of outer thermal insulating system which is under the impact of the temperature by means of theoretical analysis and test[6]. Jianda Chen and Yanfei Liang simulated the stress distribution of the polystyrene board insulating layer in outer insulating system by means of a numerical tool [7]. S. Ito, Thomas Keller, Anastasios P. Vassilopoulos, Behzad D. Manshadi discussed thermal stress of the composite lightweight structures by theoretical and experimental approaches, put forward an analysis method and acquired some test data[8].

Most of the above implemented techniques described the damage phenomenon of the plaster covering layers caused by a single factor and proposed corresponding ways to test and analyze the effect, but an outer lightweight insulating system usually works under the condition of combined effect of many factors. So, the way to test and analyze the coupling effect is the key to prevent the damage of the plaster covering layers in outer lightweight insulating system.

2. RELEVANCE OF IMPACT FACTORS

Each material in a composite structure will play a unique role. It would present different mechanics performance in the impact of an external factor. Multiple factors might be combined to exert on a composite structure at the same time, and mechanics performance of each material in a composite structure might be in diverse ways. Fig. 2 shows a typical composite wall with outer lightweight thermal insulating layer. The composite wall is constituted by a concrete basal layer, adhesive cement mortar layers, a thermal insulating layer with polystyrene board and covering plaster layers. These layers behave very differently from one another. And they differ from each other greatly in physical and mechanical properties such as thermal conductivity, coefficient of linear expansion and elastic modulus. The thermal conductivity of the cement mortar layer is approximately 22 times that of the adjacent thermal insulating layer. The elastic modulus of the cement mortar layer is about 500 times that of the thermal insulating layer. The linear expansion coefficient of the thermal insulating layer is approximately 5 times that of the cement mortar layer. The difference of physical properties among composite materials will make them in adverse state when they encounter impacts from external factors.



(a) (b)

Fig. 2 Structure and action analysis (a) Schematic diagram of composite wall with outer lightweight thermal conserving layer; (b) Schematic diagram of joint actions

During construction, the cement plaster mortar is prone to a shrinkage deformation. The deformation will produce constrained effect to adjacent structural layers and adverse effect to the cement plaster mortar layer. The in-plane tensile stress is prevalent in mortar layer.

Because the impacts from gravity, wind and temperature are usually exerted together on different layers of a composite wall with lightweight thermal insulating layer as Fig. 2 shows, the effect will present in a coupling way.

Solar heat would be easily accumulated in the covering mortar layer of a composite wall with lightweight thermal insulating layer in summer. The surface temperature could be up to 55 ℃ or above. But in case of a summer storm, the temperature might drop to 25 ℃ or lower. The temperature varies for more than 30 ℃. And temperature variation will produce a big constrained deformation and stress in covering plaster layers and thermal conserving layer. The local in-plane stress will increase significantly in covering plaster layers. Moreover, temperature variation between the internal and external sides of polystyrene board is also pretty big. It would lead to convex bending deformation which could press adjacent plaster layers and the increasing of local in-plane stress in plaster covering layer.

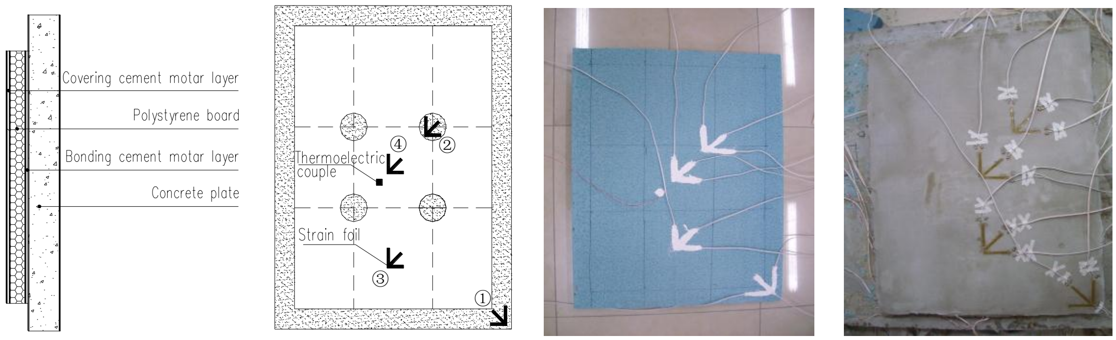
Generally, the action of wind will produce normal force on wall surface [9]. It means wind will cause out-of-plane tensile or compressive stress which is perpendicular to the plane of plaster covering layers. And the gravity force will produce vertical stress which is usually parallel to the plane of plaster covering layers. It will produce shear force between layers. The more massive a plaster covering layer, the stronger the gravity or shear force applied to it and them.

3. TEST ON THE COUPLING EFFECT

3.1. Test specimen

The specimens are made by a basal layer of reinforced concrete 60 mm in thickness, a cohesive layer of polymer mortar 3 mm in thickness, a thermal-conserving layer of plastic anchors and polystyrene board 30 mm in thickness, and a covering layer of 8 mm thick surface mortar wrapped and strengthened with alkali-resistant fiberglass mesh. The specimens are divided into two groups. One group of the covering layer is made by ordinary cement mortar. The other group is made by polymer mortar. There are three specimens in each group.

According to a mechanical feature estimated preliminarily, four positions in the surface of the covering mortar layer and the insulating layer were selected as measuring points of test respectively where the strain foils are stuck on. The strain foils are grouped and arranged at an angle of 0°, 45° or 90° with the horizontal direction as a benchmark. In addition, thermocouple elements are fixed to the edge and the middle of interfaces between different layers so that the change of temperature field could be measured. Fig. 3 shows the layout of thermocouples and strain foils.



(a) (b) (c) (d)

Fig. 3 Schematic diagram of the specimen
(a) Structure of composite wall; (b) Arrangement of the measuring point; (c) Measuring points on the surface of benzene board; (d) Measuring points on the surface of mortar

3.2. Parameters of specimen material

Performance parameters of the materials used in the production of test pieces are obtained with the method of material property testing, and the data of them are as shown in Table 1.

Table 1. Performance parameters of the material

Parameter	Ordinary mortar	Polymer mortar	Insulating board
Cube compressive strength (MPa)	36.1	11.4	-
Compression flexure ratio	5.5	2.5	-
Tensile strength (MPa)	1.4	1.1	-
Thermal conductivity（$W/(m \cdot k)$）	0.8917	0.6839	0.0362
Coefficient of thermal expansion（$^{\circ}C^{-1}$）	1.55×10^{-5}	1.27×10^{-5}	5.77×10^{-5}
Poisson's ratio	0.29	0.26	0.1
Density（kg/m^3）	2140	1753	30

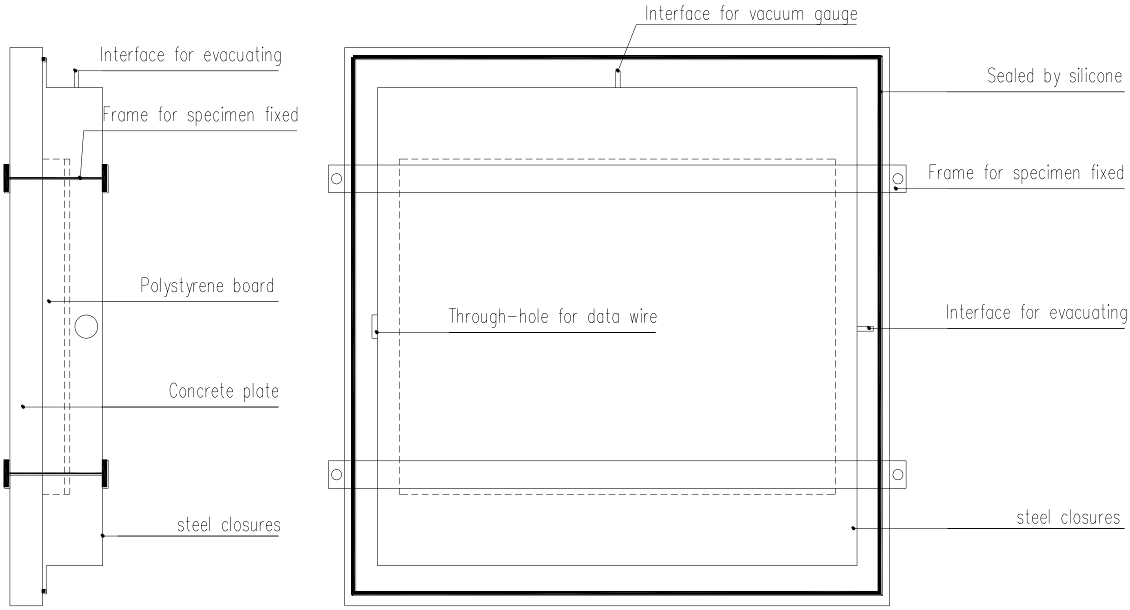
3.3. Test device

In order to test the coupling effect, a special device is designed to simulate the joint action of temperature difference, gravity and wind. As Fig. 4 shows, the device is consisted of two hot boxes and one specimen rack, which lies between the two hot boxes. The temperature difference will be simulated by the two boxes with different temperatures. The surface of a specimen could be covered with a sealing steel cap so that a cavity will be formed and the wind impact could be simulated by evacuating or pumping the cavity. The schematic diagram of the specimen installation is shown as Fig. 5

(a) (b)

Fig. 4. Device and installation of the specimen

(a) Test device; (b) Internal view of the completed specimen



(a) (b)

Fig.5. Local schematic diagram of the specimen installation

(a) A side view of the specimen with steel closure; (b) The front view of specimen with steel closure

3.4. The loading system

In the test, temperature of the low-temperature box is kept in -1 ℃. And the temperature of the high-temperature box is adjusted gradually in accordance with the test step as 25 ℃, 35 ℃, 45 ℃, 55 ℃, 65 ℃, 70 ℃ or 75℃. Evacuating or pumping the cavity to produce a certain value of pull force or pressure force by a controlling valve, the related test data are kept in record when the temperature remains stable in a preset value.

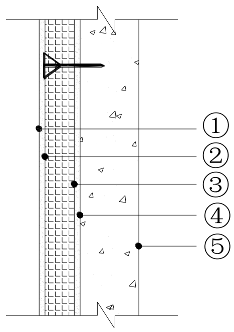
4. TESTING RESULT

4.1. Temperature distribution

Table 2 shows the surface temperature data of each structural layer of testing specimens. The distribution characteristic of temperature could be drawn as follow: the temperature difference between both sides of the insulation layer is pretty big, and the temperature difference between both sides of the mortar layer and the basal layer is pretty small. This characteristic could prove the correctness in another way that the thermal conserving layer is efficient and necessary.

Table 2 The surface temperature of each structural layer

T load level	Surface of covering mortar①	The left of the insulating board ②	The right of the insulating board ③	The left of the basal layer④	The right of the basal layer⑤	Remark
1 (18～-1)	17.5	17.3	5.4	5.4	3.3	
2 (25～-1)	22.7	22.6	5.6	5.7	3.5	
3 (35～-1)	32.0	31.5	7.9	8.1	4.6	
4 (45～-1)	39.0	38.4	10.3	10.4	5.9	
5 (55～-1)	47.3	45.4	12.4	12.5	6.7	
6 (65～-1)	56.6	54.6	12.9	13.2	7.0	
7 (70～-1)	60.2	59.3	15.3	15.5	7.2	
8 (75～-1)	65.4	64.0	16.3	16.7	7.3	



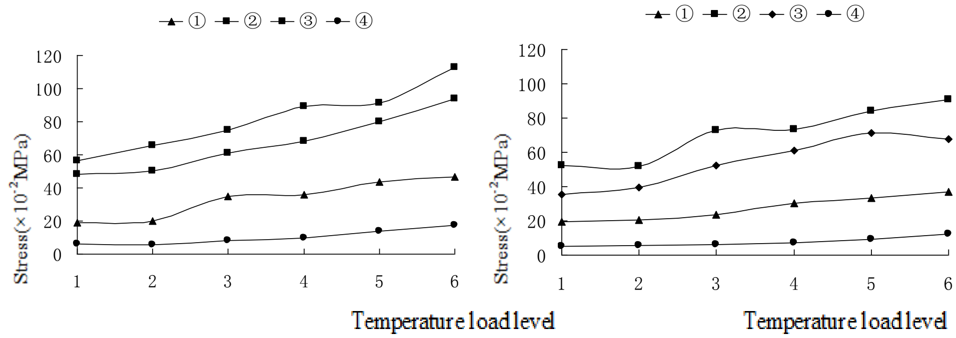
4.2. The characteristics of the stress in each layer

The characteristics of the stress are sorted out according to the strain data from the test. Table 3 shows the results of the coupling stress in the measuring position of the surface, the polymer mortar layer next to the insulating layer, the internal side of insulating layer under the combined action of gravity and wind tensile force, and the temperature difference in -1℃ (low-temperature box) or 65℃ (high-temperature box). The stress on surface of the covering mortar layer is the largest among test points at the same section. The stress on the outside surface of the insulating layer is higher than that of the inside.

Table 3. The stress of measuring points under combined action of gravity, wind tensile force and temperature difference in -1 ° C or 65 ° C

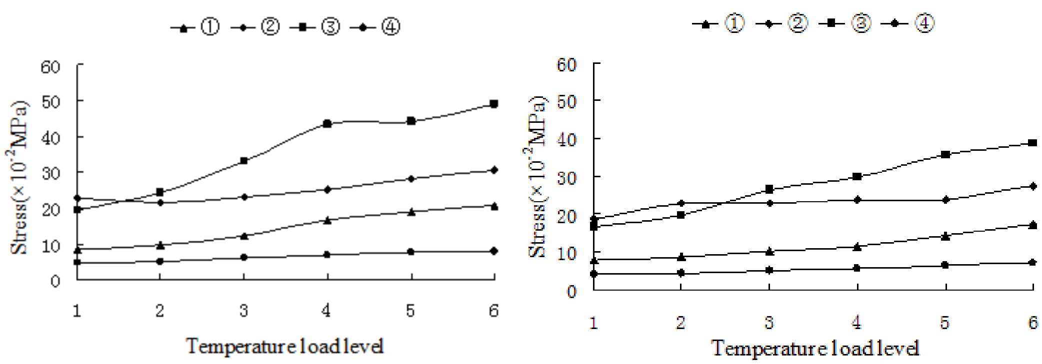
Position	Measuring point ①	Measuring point ②	Measuring point ③	Measuring point ④
The surface of the mortar layer	37.0	90.9	67.9	12.4
The left side of the insulating layer	17.5	27.5	35.7	6.3
The right side of the insulating layer	5.4	4.6	1.1	0.2

Fig. 6, 7 and 8 show the stress characteristics of each measuring point at varying temperature levels. Here, ①, ②, ③ and ④ represent the corresponding measuring point respectively in Fig. 4 (a). When temperature is up to the 7th or 8th level, the temperature of some measuring points is instable. The corresponding data of the two levels are not included in the analysis diagram for the reason of their incomparability.



(a) (b)

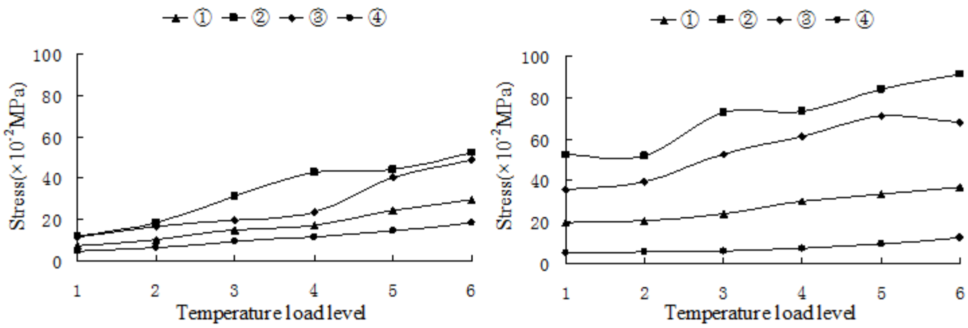
Fig. 6 Characteristics of each measuring point's coupling stress of the mortar layer's surface
(a) Ordinary mortar; (b) Polymer mortar



(a) (b)

Fig.7 The characteristics of the coupling stress of measuring points which are the internal side of the mortar next to the thermal insulating layer
(a) Ordinary mortar; (b) Polymer mortar

Fig. 6 shows characteristics of coupling stress of each measuring point of the surface of the covering mortar layer under the joint action of temperature, gravity and wind. The stress of each point goes up with the temperature increasing. The stress of measuring point ② and ③ is generally higher than that of the measuring point ① and ④.The varying amplitude of the polymer mortar's surface stress is slightly smaller than that of the ordinary mortar. Fig. 7 shows the characteristics of measuring points which are the internal side of the mortar next to the thermal insulating layer under the joint action of temperature, gravity and wind.



(a) (b)

Fig.8 Characteristics of the coupling stress of measuring points which are the internal side of the mortar next to the thermal insulating layer in the conditions of different combinations
(a) The combined effect of temperature and gravity; (b) The combined effect of temperature, gravity and wind

Fig. 8 shows the characteristics of the coupling stress of measuring points which are the internal side of the mortar next to the thermal insulating layer in the conditions of different combinations. Except for measuring point ④, the coupling stress in other measuring points increased significantly. The increased amplitude of measuring point ①, ② and ③ is 25%, 75% and 40% respectively. It can be seen easily that the impact of wind on the stress of outer lightweight thermal insulating layer in a composite wall is obvious.

4.3. Damage form of the test specimens

As shown in Fig. 9, the cracks on the covering mortar layer generally appear on each specimen. The damage symptoms on the mortar layer of specimen present corresponding features in different conditions and stages.

(1) In the early molding stage of covering plaster layer, there is no obvious crack on the surface of polymer mortar specimen, but some criss-cross cracks appear at the corner of an ordinary mortar specimen plate. If the mortar layers are strengthened and covered with fiberglass mesh, there is no obvious crack on polymer mortar specimen or ordinary mortar specimen. The causes of the appearance in early molding stage are that the shrinkage deformation of polymer mortar is smaller than that of ordinary mortar, and the shrinkage stress of the mortar layer is dispersed by fiberglass mesh [10].

(2) In the working conditions with large temperature difference, obvious cracks appear on the mortar layer, and the crack will widen and extend. The maximum of crack width is up to 0.76 mm in the test specimens. There are only micro-cracks in covering mortar layer covered and strengthened with fiberglass mesh cloth and fixed to basal layer by plastic rivets.

(3) Under joint action of temperature, gravity and wind, cracks appear on the marginal area along the edges of the covering mortar layer and the corresponding area of the covering mortar layer where a benzene board is fixed to the basal layer. Various stresses and deformations are superimposed, and their coupling effect leads to the damage of a covering mortar layer.

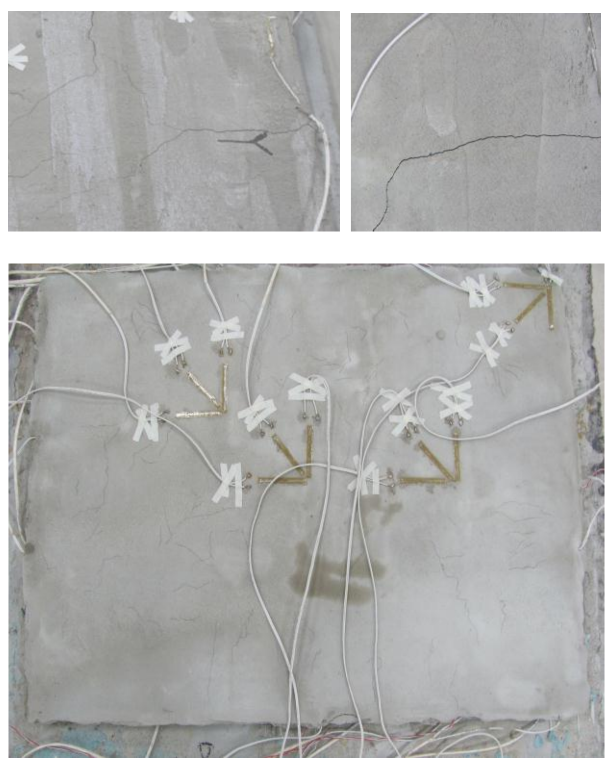
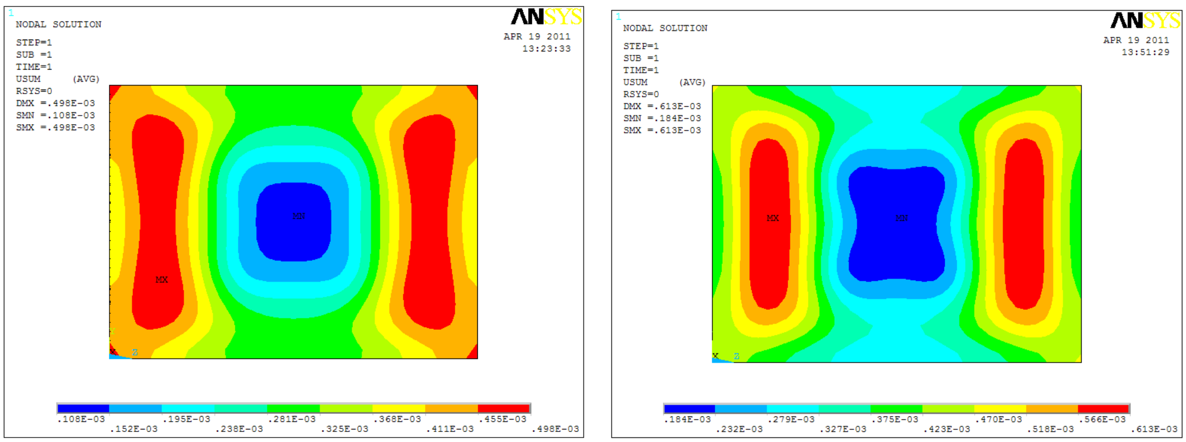


Fig 9. The facings of mortar layer in different stages

5. NUMERICAL SIMULATION

The analysis is implemented by the finite element software of Ansys. The numerical analyzing model is built based on the structure, mechanic and physical properties of material for the test specimen and the subjected actions. Two types of working conditions are simulated. One is the joint action of temperature difference and gravity. The other is the joint action of temperature, gravity and wind.

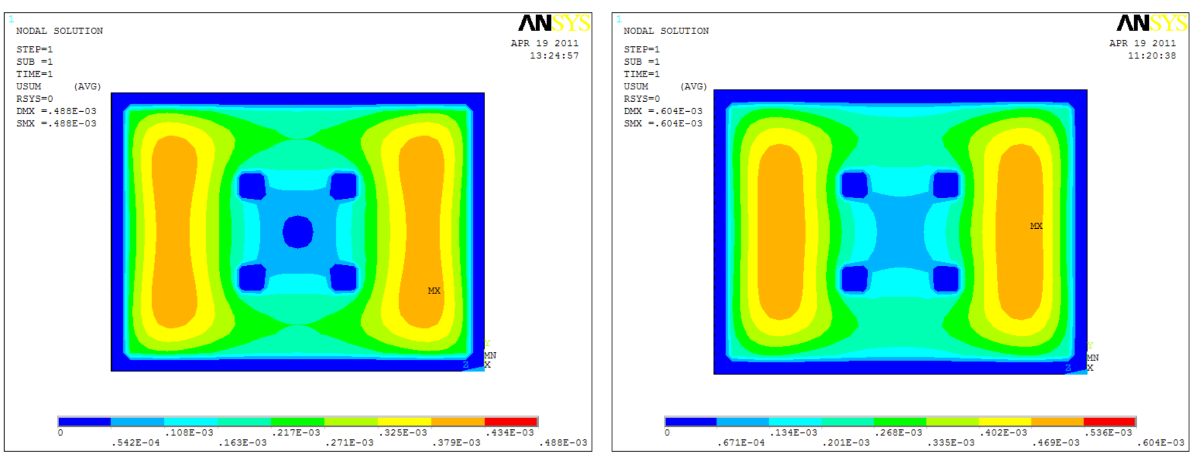
(1) The deformation contours of the covering mortar layer and thermal insulating layer in the two working condition are shown as Fig.10 and Fig.11. In the first working condition, the maximum value of in-plane deformation in the covering mortar layer is 0.498 *mm*, and that in the thermal insulating layer is 0.488 *mm*. In the second working condition, the maximum value of in-plane deformation in the covering mortar layer is 0.613 *mm*, and that in the thermal insulating layer is 0.604 *mm*. By comparison, the maximum value of in-plane deformation in the covering mortar layer or thermal insulating layer in the second working condition respectively increased 23% or 24% than in the first working condition.



(a) *(b)*

Fig.10 The deformation contours of the covering mortar layer

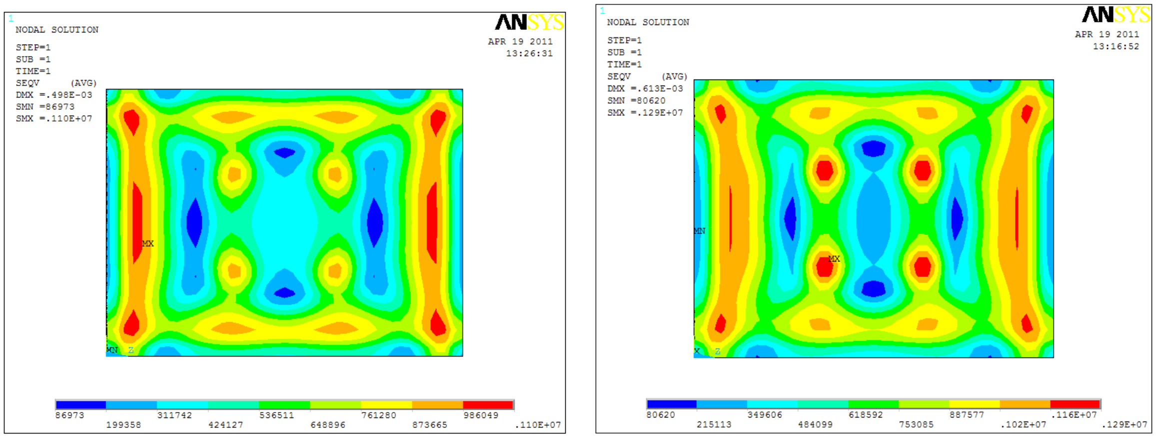
(a) In the first working condition, (b) In the second working condition



(a) *(b)*

Fig.11 The deformation contours on the internal side next to basal layer of the thermal insulation board

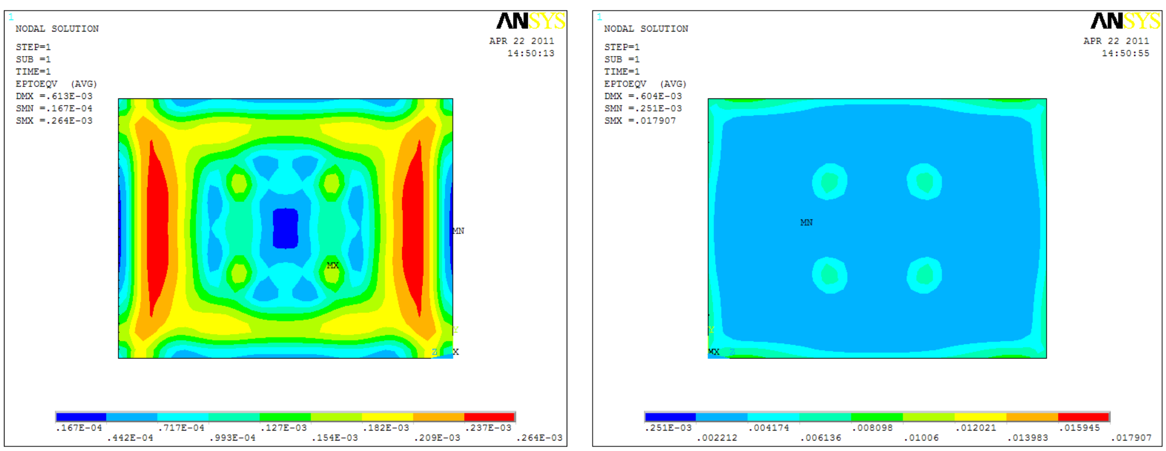
(a) In the first working condition, (b) in the second working condition



(a) (b)

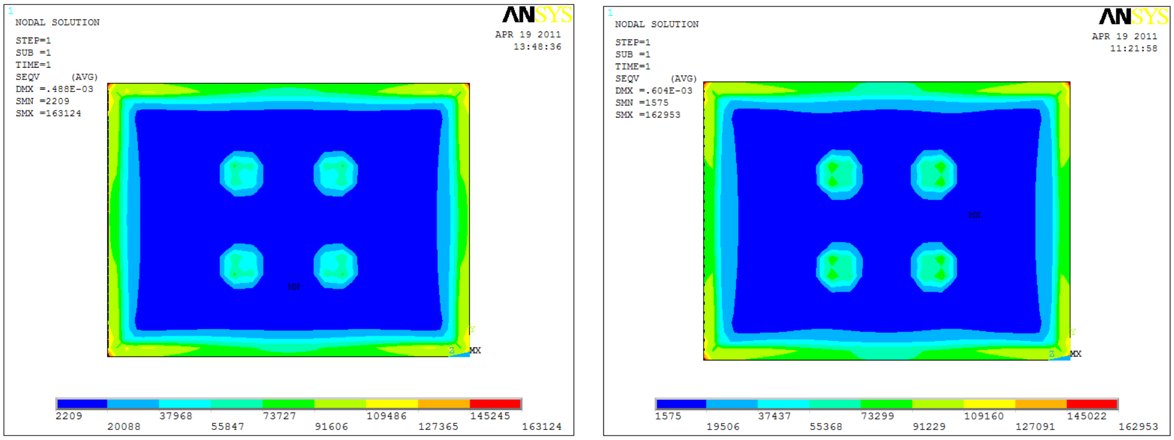
Eig.12. The stress contours of the mortar layer's surface in different working conditions
(a) In the first working condition, (b) In the second working condition

(2) The stress or strain contours of the covering mortar layer and thermal insulating layer in the two working condition are shown as Fig.12, 13 and 14. (a) The stress in the marginal area along the edges of the covering mortar layer and the corresponding area of the covering mortar layer where a benzene board is fixed to the basal layer higher than others. (b) The stress value of in-plane deformation in the covering mortar layer under the second working condition is higher than the first working condition. (c) The maximum value of strain in the covering mortar layer is 264$\mu\varepsilon$. The corresponding maximum value of strain in the benzene board layer is 2212$\mu\varepsilon$.



(a) (b)

Fig.14. Strain contours
(a) The covering mortar layer; (b) The internal side next to basal layer of the thermal insulating layer



(a) *(b)*

Fig.13. The stress contours on the internal side next to basal layer of the thermal insulation board (a) In the first working condition, (b) In the second working condition

6. CONCLUSIONS

The present study shows that: (1) Coupling effect under the joint action of temperature difference, gravity and wind will increase the deformation and stress in each layer of a composite wall with lightweight thermal insulating layer. (2) The strain in the covering mortar layer is much higher than that in the thermal conserving layer. The cause is that the covering mortar layer is subjected the action from multiple factors. Greater temperature difference results in bigger in-plane stress in the covering mortar layer. Greater temperature difference between two sides of the thermal conserving layer makes the thermal conserving layer bending which could intensify the stress in the covering mortar layer. (3) As the maximum value of the coupling principle tensile stress in the covering mortar layer exceeds the strength of mortar, the covering mortar layer would be damaged. The crack would be extended and widened as the coupling effect being intensified.

7. ACKNOWLEDGEMENTS

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