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Finite Element Study on Mechanical Performances of Multi-Span Metal Faced Sandwich Panels under Temperature Actions

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Abstract. Metal faced sandwich panel is composed of two relatively high strength metal faces and a relatively thick and lightweight insulated core. Under the continuous action of temperature such as strong sunlight, the multi-span metal faced sandwich panels can be destroyed. In this paper, the finite element (FE) software ABAQUS was used to study the stress and deformation of these sandwich panels under temperature action. The FE results show that the compressive stress in the mid-span region of the metal panel is larger and it gradually decreased from the middle to the two sides. The deformation at the centre of side span of sandwich panels is larger. The support constraints at the bottom of the sandwich panel have a great influence on the temperature stress. The fixed sandwich panel is more likely to occur wrinkle failure than the hinged one. To reduce the effects of temperature, two effective methods are proposed. The method increasing the density of the core material can increase the buckling stress and improve the bearing capacity against temperature action. The other method reducing the length of each segment of the sandwich panel can effectively release the temperature stress and reduce the negative effects of temperature.

1. Introduction

The typical sandwich panel used in building has a three-layer structure. As shown in Figure 1, the metal faced sandwich panel is composed of two relatively high strength metal faces and a relatively thick and lightweight insulated core. It is extensively used in many energy-efficient buildings for its many advantages such as high load-bearing capacity at low weight, excellent thermal insulation and rapid erection.

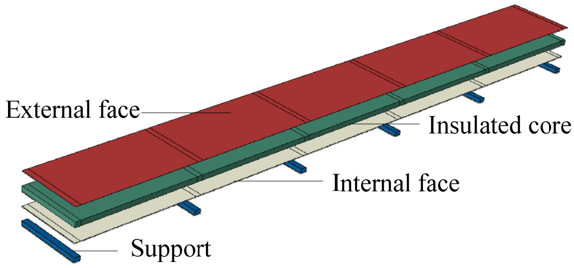

Figure 1. Multi-span metal faced sandwich panels.

For buildings, the temperature effects caused by changes in natural environmental conditions can generally be divided into three categories: sunshine temperature, sudden cooling temperature and annual temperature. Among them, the temperature effect of sunshine on the external face of metal sandwich panel is the most significant. The maximum temperature of sandwich panel with dark colour can up to 80℃ which is pointed out by *European Recommendations for Sandwich Panels*[1].

For the metal face with faster heat conduction rate, it is sensitive to the change of temperature. Under the continuous action of temperature such as strong sunlight, the heat absorbed by the external metal face cannot be conducted and diffused through the intermediate heat insulating core material. This situation can cause a large amount of heat to accumulate in the metal face and a large temperature difference load effect is produced on the internal side and the external side of the multi-span metal faced sandwich panel, which causes the sandwich panel destroyed finally.

In the past, the length of metal faced sandwich panels used in engineering is mostly 6m or less, and the number of spans is mostly three or less. In recent years, with the improvement and application of sandwich panels technology, the length of metal faced sandwich panels used in engineering increases from 6m to 12m, and their span number also increases from four to six. As the length of the metal faced sandwich panel used in buildings gradually increases, multiple supports need to be added under the sandwich panel to reduce the effects of wind loads. However, this causes the temperature stress of the metal panel to be difficult to release, causing a large increase in stress and deformation, and eventually destruction. After the damage due to temperature, the bearing capacity of the sandwich panel is greatly reduced, and it is difficult to resist direct loads such as strong winds, and even cause safety accidents such as falling of the sandwich panel at high altitude.

Up to present, there have been some studies on the mechanical properties of sandwich panels under direct loads such as wind and snow loads in references [2-9]. However, the related study on metal faced sandwich panels under indirect loads such as temperature action is very few. Based on the classical theoretical analysis model of sandwich panels, the theoretical calculation formulas of single-span to three-span metal-faced sandwich panels under temperature are obtained by Davies [10], but these theoretical formulas below three-span have not been tested or verified by finite element method. Qin [11] carried out experimental research on single-span and double-span metal-faced sandwich panels under temperature. It was found that large bending deformation occurred in single-span sandwich panels, but no obvious damage occurred, while local buckling occurred in the middle of double-span sandwich panels. Li [12] used the energy method to solve the theoretical calculation formulas of the end axial restraint force and mid-span deflection of single-span metal faced sandwich panels under temperature and uniform load, and carried out experiments and finite element analysis. Zhu [13] studied the internal force distribution and transfer law of two-span and three-span sandwich panels and simplified the calculation formula by introducing stiffness coefficient.

Figure 2. Destruction phenomenon of metal faced sandwich panels under temperature action.

As mentioned above, most of these studies focused on mechanical properties of single-span and double-span metal sandwich panels rather than the mechanical properties of multi-span metal sandwich panels with more than three spans under temperature actions. However, at present, due to lack of study on the mechanical properties of multi-span sandwich panel under temperature action, there is no adequate useful design basis for multi-span metal sandwich panels. These reasons lead to some problems in engineering design and application. In recent years, some multi-span metal faced sandwich panels have been seriously damaged, which have affected the service function and architectural appearance of buildings and even cause serious economic losses and casualties. For example, in 2017, many multi-span sandwich panels have been seriously damaged by strong sunlight which causes large temperature effect in an industrial plant engineering project in Tianshui City, China. Some destruction phenomenon is shown in Figure 2.

In order to provide some useful referential basis for the engineering design and application, according to the above mentioned actual engineering project, this paper mainly studied the mechanical properties of multi-span metal sandwich panel under temperature action by finite element (FE) method.

2. Finite element method

2.1 Geometric sizes and materials

The geometric sizes and materials of the metal face sandwich panel were determined by the actual sizes and materials used in the above mentioned actual engineering project. The sandwich panels with 6m length and 3 spans, 7.2m length and 4 spans, 9m length and 5 spans under temperature actions were simulated by FE method. The total thickness of the sandwich panel was 75mm. The external face is a 0.6mm thick steel plate and the internal face was a 0.5mm thick steel plate. The intermediate insulation core layer was 73.9mm thick glass wool. The bottom supports were made of square steel pipes with a section of 80mm × 60mm × 2mm. The width of every sandwich panel is 1m.

2.2 Finite element model and boundary conditions

As shown from Figure 3 to Figure 5, the FE models of the sandwich panel with different lengths and spans were built with the software ABAQUS.

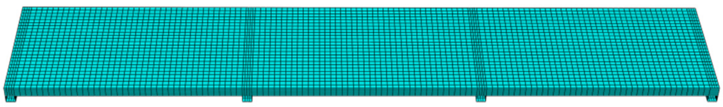

Figure 3. FE model of sandwich panel with 6m length and 3 spans.

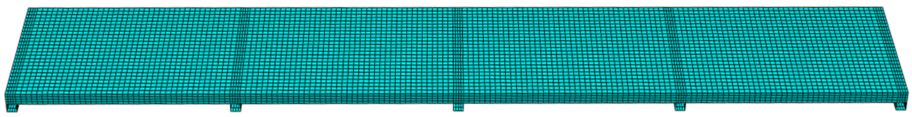

Figure 4. FE model of sandwich panel with 7.2m length and 4 spans.

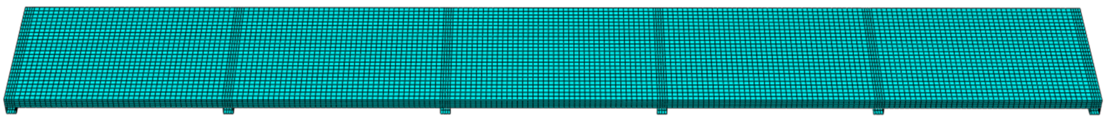

Figure 5. FE model of sandwich panel with 9m length and 5 spans.

In the FE models, the steel faces and square steel tube supports whose thickness is relatively thin were modeled with shell elements of type S4R. The glass wool (GW) core whose thickness is relatively thick was modeled with solid elements of type C3D8R with isotropic material models. They were assumed to be isotropic liner elastic material. The material properties of the steel face and the glass wool core used for FE analysis are shown in Table 1. The material properties of the steel refer as Chinese national standards for design of steel structures [14].

Table 1. Material properties in FE model of the sandwich panel.

Material type	Density (kg/m^3)	Elastic Modulus (MPa)	Poisson's ratio	Expansion coefficient (10^{-5}/℃)
Glass wool	64	2.49	0.17	—
Steel	7850	2.06×10^5	0.30	1.20

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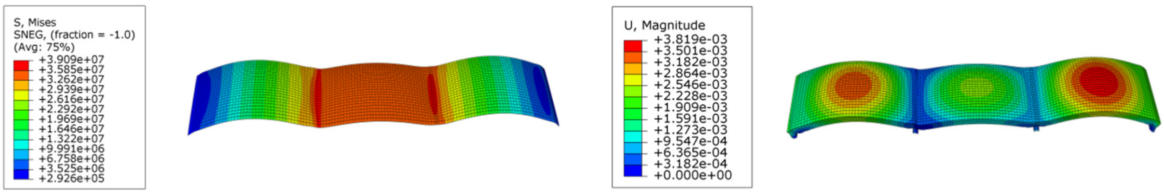
It has been assumed that the face and the core are perfectly bonded together, and the faces have no slippage occurs relative to the core. Therefore, the constrained type of the interaction among steel face, glass wool core and square steel tube supports was set to "tie contact", which just was the same as merging coincident nodes. At the interface, the faces were treated as master surfaces and the core surfaces were treated as slave surfaces. The faces were firmly tied to the core surface. Hence, the DOFs (degrees of freedom) of the nodes on faces and core could keep compatible with each other in FE analysis. The sandwich panel with hinged support constraints and fixed support constraints were studied. In hinged supports constraints, the steel pipe at one end was fixed and the other steel pipe can slide horizontally. In fixed supports constraints, the surrounding of steel pipes at both ends was fixed, and the bottom of the middle rafter was fixed.

According to the actual measured temperature and the maximum temperature specified by *European Recommendations for Sandwich Panels* [1], the temperature of internal face was set to 25℃ constant temperature, and the temperature of external face was heated to 60℃and 80℃ under sunlight. To simulate this temperature difference between external face and internal face, the same room temperature to all sandwich panels and supports was applied first, keeping the internal face at 25℃, then the external face was raised to the target temperature.

3. Results and discussion

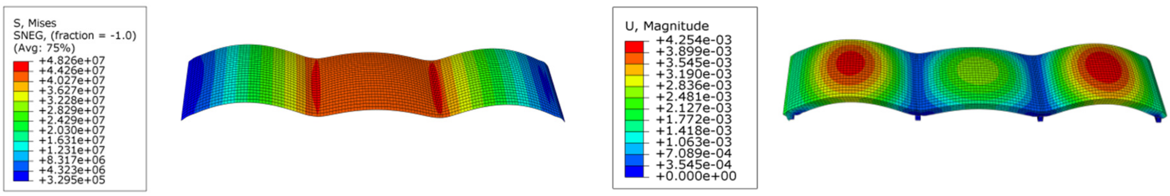
3.1 Temperature stress and deformation distribution

As shown in Figure 6 to Figure 11, the stress and deformation distribution of the sandwich panels with different lengths, spans and supports are similar. Under the temperature action, the compressive stress in the mid-span region of the metal panel is larger, which gradually decreased from the middle to the two sides. The deformation at the centre of side span of sandwich panels is larger. The compressive stress of the metal panel near the supports in the central area is larger. For 5 spans sandwich panels, the larger stress region of FE simulation shown in Figure 11 is essentially the same as the destruction region of the preceding actual engineering shown in Figure 2, which proves that the FE simulation results is reasonable and reliable.



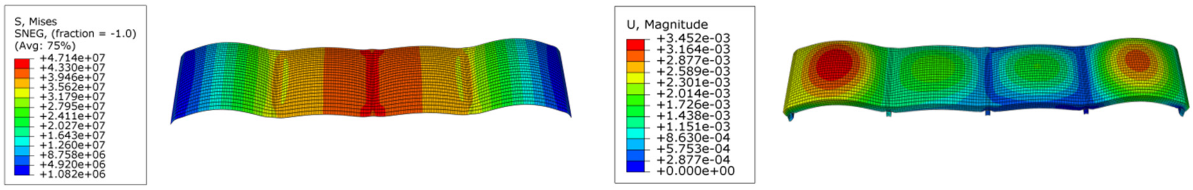
(a) Stress of external face. (b) Deformation of sandwich panel.

Figure 6. Stress and deformation for hinged sandwich panel with 6m length and 3 spans.



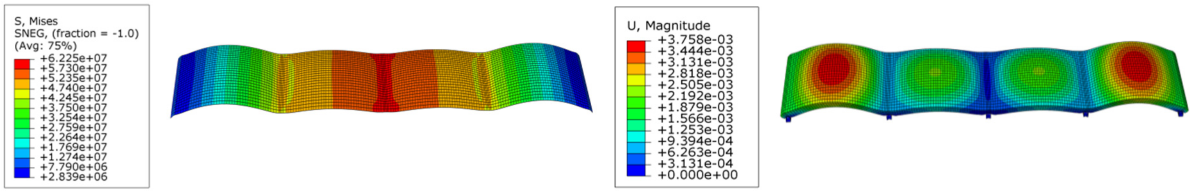
(a) Stress of external face. (a) Stress of external face.

Figure 7. Stress and deformation for fixed sandwich panel with 6m length and 3 spans.



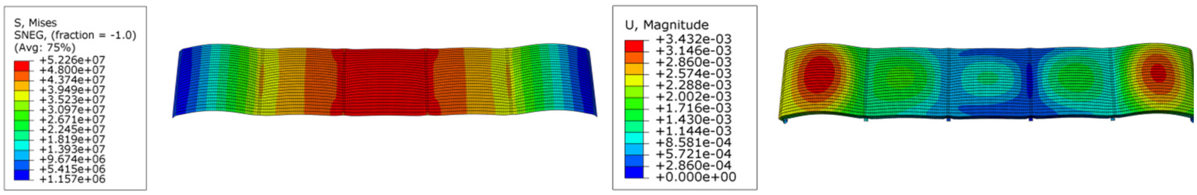
(a) Stress of external face. (b) Deformation of sandwich panel.

Figure 8. Stress and deformation for hinged sandwich panel with 7.2m length and 4 spans.



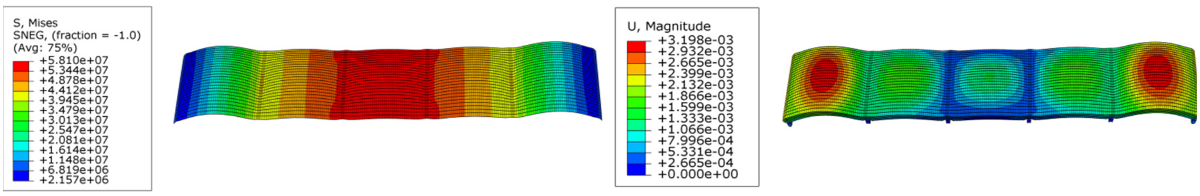
(a) Stress of external face. (b) Deformation of sandwich panel.

Figure 9. Stress and deformation for fixed sandwich panel with 7.2m length and 4 spans.



(a) Stress of external face. (b) Deformation of sandwich panel.

Figure 10. Stress and deformation for hinged sandwich panel with 9m length and 5 spans.



(a) Stress of external face. (b) Deformation of sandwich panel.

Figure 11. Stress and deformation for fixed sandwich panel with 9m length and 5 spans.

3.2 Temperature wrinkling stress

As shown in Figure 12, under the temperature actions, the multi-span metal sandwich panels expand and bend, while the supports restrain the deformation of the sandwich panels in the opposite direction and produce the corresponding reverse tension. At the same time, the bending moment of the sandwich panels cause the compression of the heated external face and the tension of the internal face. Under the compression load caused by temperature action, the thin face whose thickness is usually less than 1 mm may produce wrinkle local buckling failure, as shown in Figure 13. The unique local buckling failure phenomenon of the thin faced sandwich panel is also simply called wrinkle failure. This kind of failure is similar to the lateral instability of the compressive member in steel structure, but the difference is that the core material of sandwich panels provides the lateral cushion stress for the metal face, which can prevent its premature instability. Wrinkle failure usually occurs abruptly while the temperature stress during the failure has not reached the yield strength of the metal face plate. This failure always occurs in the compressed face.

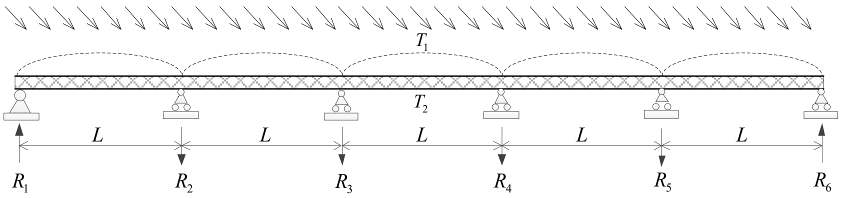


Figure 12. Multi-span metal sandwich panel under temperature action.

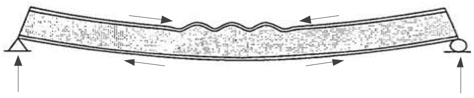


Figure 13. Wrinkle failure of metal faced sandwich panel.

According to *European Recommendations for Sandwich Panels*[1], the wrinkling stress σ_{wr} of a flat metal face may be calculated using

$$\sigma_{wr} = k\sqrt[3]{E_{CT}G_{CT}E_F} \quad (1)$$

Where E_{CT} = mean value of the elastic modulus of the core, G_{CT} = mean value of the shear modulus of the core, E_F = elastic modulus of metal face. The coefficient k is a constant less than 0.82 and can be determined experimentally for a particular product. The range of the constant k has been found to be appropriate from 0.5 to 0.65 for the metal faced sandwich panels with different cores. For GW cores, the applicable value of k is 0.5.

Assuming that the face and core materials of the metal faced sandwich panels are isotropic elastic materials. For the sandwich panels with GW cores, G_{CT}=1.07MPa, E_{CT}=2.49MPa, E_F=2.06×10^{5}MPa, substitution of these parameters into equation (1) gives σ_{wr} = 40.93MPa. When the compressive stress of the face under temperature action is very close to the wrinkling stress σ_{wr} or greater than that, the face of sandwich panel is considered to be partially unstable and wrinkle failure occurs. The results of FE method are summarized as shown in Table 2.

Table 2. FE analysis results.

Serial number	Total length (m)	Span number	Support constraint	Temperature (℃)	Max. stress (MPa)	Wrinkle Failure
1-1	6	3	Hinged	60	25.76	No
1-2	6	3	Hinged	80	40.48	Yes
1-3	6	3	Fixed	60	31.73	No
1-4	6	3	Fixed	80	49.86	Yes
2-1	7.2	4	Hinged	60	30.77	No
2-2	7.2	4	Hinged	80	48.36	Yes
2-3	7.2	4	Fixed	60	40.52	Yes
2-4	7.2	4	Fixed	80	63.60	Yes
3-1	9	5	Hinged	60	33.97	No
3-2	9	5	Hinged	80	53.38	Yes
3-3	9	5	Fixed	60	48.07	Yes
3-4	9	5	Fixed	80	59.27	Yes

As shown in Table 2, with the increase of length and the number of spans, the stress increases. The constraints of supports at the bottom of the sandwich panel have a great influence on the temperature stress. Compared with the temperature stress of articulated restraint, the temperature stress of fixed restraint can be increased by about 1.45 times. This means that the fixed sandwich panel is more likely to occur wrinkle failure than the hinged one.

3.3 Improvement measures

From the above results FE analysis, it can be seen that the main cause of the sandwich panel damage is that the temperature stress caused by the temperature difference action between external face and internal face. The excessive constraints of support restraint make it more difficult to release temperature stress of the long metal face. Hence, the total temperature stress exceeds the wrinkling stress of the sandwich panel and wrinkle failure occurs. Therefore, it is necessary to study the improvement measures to increase the wrinkling stress bearing capacity or release the temperature stress of sandwich panels.

As shown in equation (1), the wrinkling stress is related to the elastic and shear modulus of core and the elastic modulus of face. The face is usually made of steel and the elastic modulus of steel face is basically the same. But the difference of the elastic and shear modulus of cores is big. These mechanical properties of core materials are always directly related to density. The density of cores is greater, the elastic and shear modulus of cores are higher. Increasing the core density will increase the wrinkling stress of the face.

For the previous FE model of sandwich panel with 9m length, in scheme A, the glass wool with density of 64kg/m^3 was changed to rock wool with density of 100kg/m^3. In scheme B, the glass wool was changed to rock wool with density of 150kg/m^3. The other conditions remain unchanged in the same FE model. The FE analysis results are shown in Table 3.

Table 3. Results of increasing core density.

No.	Density (kg/m^3)	Support constraint	Temperature (℃)	Max. stress (MPa)	Increase ratio （%）	Wrinkle stress (MPa)	Increase Ratio （%）	Wrinkle Failure
A-1	100	Hinged	60	38.12	12.22	57.71	41.00	No
A-2		Hinged	80	59.90	12.21			Yes
A-3		Fixed	60	57.83	20.30			Yes
A-4		Fixed	80	67.72	14.26			Yes
B-1	150	Hinged	60	40.47	19.13	75.63	84.78	No
B-2		Hinged	80	63.60	19.15			No
B-3		Fixed	60	64.30	33.76			No
B-4		Fixed	80	72.76	22.76			No

From the Table 3, it can be concluded that with the increase of core density, both the maximum temperature stress and wrinkle stress of the panel increase, but the increase amplification of wrinkle stress is greater than increase amplification of the temperature stress. With the increase of core density, the wrinkling stress of face increases. This means that the sandwich panel with cores of greater density has a higher wrinkling bearing capacity against temperature action.

If the length of the sandwich panels is too long, it is difficult to release temperature stress, especially for multi-span sandwich panels with excessive constraints of supports. Hence, another improvement measure is to cut off the long sandwich panels and reduce the length of each panel to release temperature stress. For the previous FE model of sandwich panel with 9m length, the cut-off location of both scheme C and scheme D is on the centre line of length. The scheme C didn't add square steel pipe support at the cut-off location. The scheme D added square steel pipe support at the cut-off location. The other conditions remain unchanged. As shown in Table 4, it can be concluded that both scheme C and scheme D can reduce the temperature stress effectively, but the effect of scheme C is better than that of scheme D.

Table 4. Results of reducing the length of each panel.

No.	Support constraint	Temperature (℃)	Max. stress (MPa)	Decrease ratio （%）	Wrinkle stress (MPa)	Wrinkle Failure
C-1	Hinged	60	17.43	-48.69	40.93	No
C-2	Hinged	80	27.39	-48.69		No
C-3	Fixed	60	17.99	-62.58		No
C-4	Fixed	80	28.28	-52.29		No

D-1	Hinged	60	20.38	-40.01	40.93	No
D-2	Hinged	80	32.03	-40.00		No
D-3	Fixed	60	23.68	-50.74		No
D-4	Fixed	80	37.21	-37.22		No

4. Conclusions

This paper studied on the mechanical properties of multi-span metal faced sandwich panel under temperature action by FE analysis method. The main conclusions of this study are drawn as follows.

(1) Under the temperature action, the compressive stress in the mid-span region of the metal panel is larger, which gradually decreased from the middle to the two sides. The deformation at the centre of side span of sandwich panels is larger.

(2) The constraints of supports at the bottom of the sandwich panel have a great influence on the temperature stress. The fixed sandwich panel is more likely to occur wrinkle failure than the hinged sandwich panel.

(3) Increasing the density of the core material can increase the buckling stress of the panel and improve the bearing capacity of the sandwich panel against temperature.

(4) Reducing the length of each segment of the sandwich panel can effectively release the temperature stress and reduces the negative effects of temperature.

Acknowledgments

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