Influence of Intense Solar Radiation on Long-span Steel Structures

Jiayi Mao¹, Jianchun Xiao²,³ *, Hanming Zhang²,³ and Tao Tang²,³

¹Guiyang City People’s Air Defense Office, Guiyang, China
²Space Structures Research Center, Guizhou University, Guiyang 550003, China
³Key Laboratory of Structural Engineering of Guizhou Province, Guiyang, China

*Corresponding author e-mail: jcxiao@gzu.edu.cn

Abstract. The temperature distribution of a long-span structures is not uniform due to solar radiation. Assumptions of uniform and nonuniform temperature field make the analysis results different. A mathematical model of solar radiation is established to calculate the hourly radiation intensity on the surface of a building at any geographical location. The temperature distribution of a 100m span spherical reticulated shell located in Guiyang city in China is calculated. The mechanical performance of the structure is analysed by finite element method. The following results gives: 1. the highest temperature is 48.5°C and the lowest temperature is 23.0°C. 2. The nonuniform temperature distribution makes the deformation of the reticulated shell no longer symmetrical.

1. Introduction

The external temperature distributions of long-span structures are not uniform when exposed to solar radiation. The temperature of the shadow zone is lower than the temperature of the irradiation zone. The thermal insulation of the covering material of some large-span spatial structures is limited. Assumptions of uniform and nonuniform temperature field lead to different analysis results. The frequency coefficient of solar radiation is high. The temperature change has a significant effect on the large-span structural safety and the amount of steel used.

There are many articles explaining the influence of temperature on different building structures, such as masonry structure, long-span concrete beam and space truss structure, etc. [1-3]. Fan introduced the structural design of China National Stadium [4,5]. Based on the statistical data of the past 30 years, the maximum positive temperature difference and the maximum negative temperature difference are calculated according to the heat absorption condition of the surface material. This simplified temperature field distribution is different from the reality. Kimura, Fu and Chen proposed the calculation methods of solar radiation intensity on the surface of buildings respectively [6-8]. These methods are widely used in transient heat conduction analysis of buildings or structures. Pei analyzed the solar radiation effect of A380 hangar of Beijing Capital International Airport, and the conclusion is that the influence of nonuniform temperature field on the structure should not be neglected [9].

We use simplified method to simulate the external temperature field of a large-span reticulated spherical shell under solar radiation. The finite element method is used to analyze the mechanical properties of reticulated shells under temperature distribution.
2. Computational theory
Solar radiation causes the temperature of the building's covering to change with time. Heat exchange exists between buildings and environment. When the influence of wind speed is ignored, the total solar radiation intensity obtained on the covering of a building consists of direct radiation and scattered radiation. Total solar radiation intensity \( I_t \) is expressed as

\[
I_t = I_D + I_{ds} + I_{dg}
\]

Where \( I_D \) is solar direct radiation intensity, \( I_{ds} \) is sky scattering radiation intensity, and \( I_{dg} \) is ground reflection radiation intensity. \( I_D \) is also be expressed as

\[
I_D = I_{DN} \cos \theta
\]

Where \( I_{DN} \) is direct solar radiation intensity, \( \theta \) is the angle between the light rays and the earth surface normal. Establishing a mathematical model of direct solar radiation gives the hourly radiation intensity on the surface of buildings at any geographical location. For medium roughness building coverings, the convective heat transfer coefficient \( h_c \) \((\text{W} / (\text{m}^2 \cdot ^\circ \text{C}))\) of the outer surface is calculated according to the following approximate formulas

\[
h_c = 4.2v + (2.5 \sim 6.0)
\]

Where \( v \) \((\text{m/s})\) represents wind speed, constant term is used to reflect the effect of natural convection heat transfer.

3. Calculation of temperature field
A rib-ring spherical reticulated shell in Guiyang city in China is selected as an example. The covering is profiled steel sheets and coated with light-colored paint. It has a span of 100m, a height of 50m and a thickness of 3m. Hinged bearings are arranged with a distance of 6.3m along the periphery. Constant load is 0.3kN/m\(^2\) and live load is 0.5kN/m\(^2\).

The specific heat, thermal conductivity and emissivity of the covering material are determined according to the material handbook. Radiation intensity, angle and time are simply replaced by the geographic location of buildings. Assume that the sun shines at 60 degrees in the area where the building is located. Considering the influence of coating color and surface grey of profiled steel sheet, the absorption coefficient is 0.6. The atmospheric transparency is 0.8.

The total solar radiation in the irradiation area is 1125W/m\(^2\), and the total solar radiation in the shadow area is 100W/m\(^2\). Assume they change by the following formula

\[
I_{(t_1)} = I_{(t_2)} \cos \left[ \frac{\pi}{14} (t - 12) \right], \quad t \in [5, 19]
\]

Where \( t \) is time in hours.

The wind speed \( v \) is 0.5m/s. The initial temperature is 18\(^\circ\)C. In addition to considering the heat absorption of covering, the material's radiation to the surrounding environment is calculated by the material's radiation rate. It is considered that the absorption capacity of the surrounding environment is infinite.

The maximum temperature difference of the example is at \( t = 15.5h \). The temperature distribution of the covering is shown in Figure 1. The highest temperature is 73.6\(^\circ\)C, the lowest temperature is 28.0\(^\circ\)C, and the average temperature is 50.8\(^\circ\)C.
4. Coupled thermal-stress calculation
Consider the following four working conditions respectively:
case 1: dead + live
case 2: dead + live + uniformly distributed temperature (average temperature)
case 3: dead + live + uniformly distributed temperature (maximum temperature)
case 4: dead + live + nonuniformly distributed temperature at $t=15.5h$

The axial forces of upper and lower chord members under different working conditions are shown in Figures 2 to 5.
The maximum/minimum axial force and the maximum horizontal reflection at supports are shown in Table 1.

**Table 1.** Maximum and minimum axial force and the maximum horizontal reflection at supports

| cases | 1     | 2     | 3     | 4     |
|-------|-------|-------|-------|-------|
| Maximum axial force / kN   | 13.9  | 53.3  | 85.8  | 89.4  |
| Minimum axial force / kN    | -79.9 | -164.5| -262.0| -267.6|
| Maximum horizontal reflection at supports / kN | 19.8  | 28.5  | 33.3  | 32.5  |
The influence of solar radiation on the internal force of the members is obvious. Compared with case 3, the axial force absolute value of almost the members in the sunny area of case 4 is larger. For case 4, the axial force absolute value of the member located in the sunny area is much greater than that of the backlight area. With the increase of temperature difference, the horizontal reaction force at the support increases. With the increase of temperature difference, the vertical displacement of double-layer reticulated shell joints decreases while the horizontal displacement increases. The vertical displacement in case 4 is shown in Figure 6. The deformation of reticulated shells with inhomogeneous temperature field is no longer symmetrical.

5. Conclusion
Simplified method is used to simulate the temperature field of large-span space steel structure under solar radiation, and the distribution of the temperature field of a spherical reticulated shell roof in Guiyang city in China is obtained. Finite element method is used to analyze the effect of external non-uniform temperature field on the mechanical properties of reticulated shells.

The case study shows that the assumption of uniform temperature distribution is not completely applicable to the design of long-span spatial steel structures. The non-uniform temperature field makes the internal force of the structural member change obviously, and the increase of the axial force of the member in the positive area is larger. The simplified method of selecting the highest temperature value of the structure and applying it evenly on the surface of the structure is compared with the actual results. The former has a slightly smaller axial force in the positive area than the latter, while the latter has a greater axial force in the negative area. In the design of double-layer latticed shells, it is suggested that the non-uniform temperature field should be used as far as possible.

Acknowledgments
This work was financially supported by Guizhou Natural Science Foundation (QRF 2017-01, 2017-1054-1036).

References
[1] L. J. Pan, B. G. Xu, X. J. Yan, etc, Temperature field of masonry structure considering solar radiation, Journal of Zhejiang University (Engineering Science). 2002, 36(5) 577-581.
[2] J. Wang, Y. Yang. Static analysis of large-span prestressed concrete continuous rigid-frame, Sichuan Building. 2007, 27(1) 135-137.
[3] Y. Ding, H. Q. Han, H. W. Cheng, etc, Design of the space girder trestle for heat-supply-pipe across west main line in Daqing, Journal of Building Structures. 2001, 22(5) 66-69.
[4] Z. Fan, M. X. Liu, W. X. Fan, etc, Design and research of large-span steel structure for the National Stadium, Journal of Building Structures. 2007, 28(2) 1-16.
[5] Z. Fan, Z. Wang, J. Tang, Analysis on temperature field and determination of temperature upon healing of Large-span steel structure of the National Stadium, Journal of Building Structures. 2007, 28(2), 32-40.
[6] K. Kimura, The scientific basis for air-conditioning. Beijing: China Architecture & Building Press. 1981.
[7] Z. X. Fu, Building energy-saving technology at hot summer and cold winter area in China, Beijing: China Architecture & Building Press. 2002.
[8] H. C. Chen, M. E. Krokosky. Steady and non steady solar heat transmission through roofs, Materials and Structures, 1976, 9(1) 19-32.
[9] Z.Y. Pei, Y. Bai, J. Y. Shi, D. Zhu, Q. Y. Wang, Temperature distribution in a long-span aircraft hanger, Tsinghua Science and Technology. 2008, 13(2) 184-190.