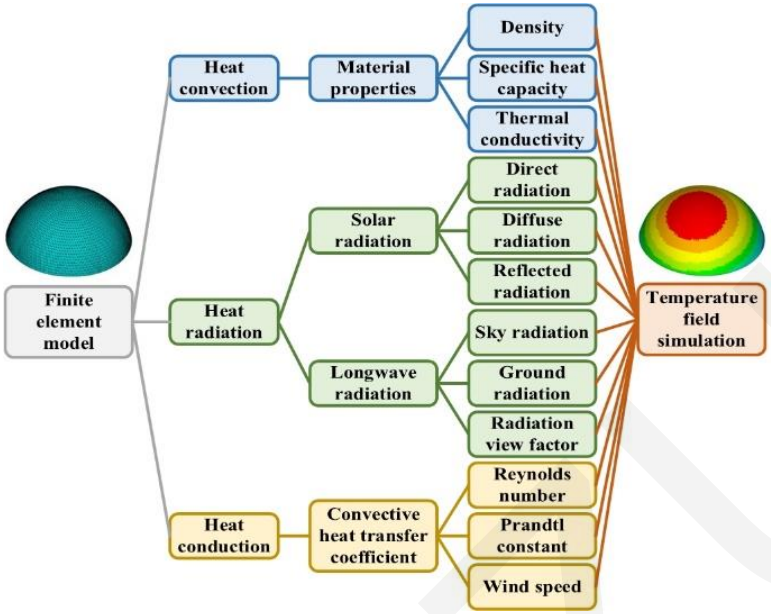
Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)

Non-uniform thermal behavior of single-layer spherical reticulated shell structures considering time-variant environmental factors: analysis and design

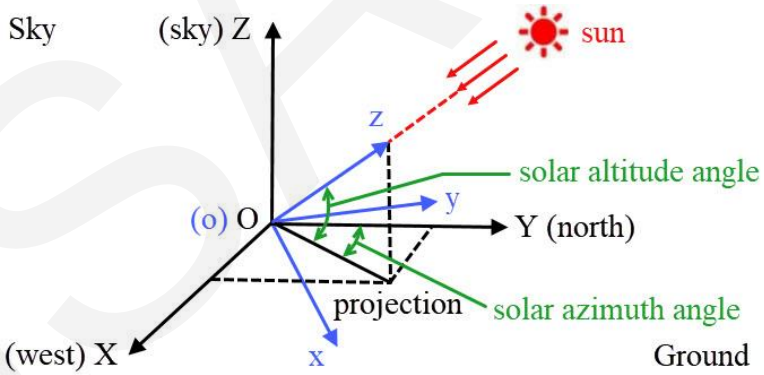
Wucheng XU, Xiaoqing ZHENG, Xuanhe ZHANG, Zhejie LAI, Yanbin SHEN

Cite this as: Wucheng XU, Xiaoqing ZHENG, Xuanhe ZHANG, Zhejie LAI, Yanbin SHEN, 2024. Non-uniform thermal behavior of single-layer spherical reticulated shell structures considering time-variant environmental factors: analysis and design. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 25(3):223-237. https://doi.org/10.1631/jzus.A2300143

Simulation of non-uniform temperature field



Numerical simulation process of temperature field

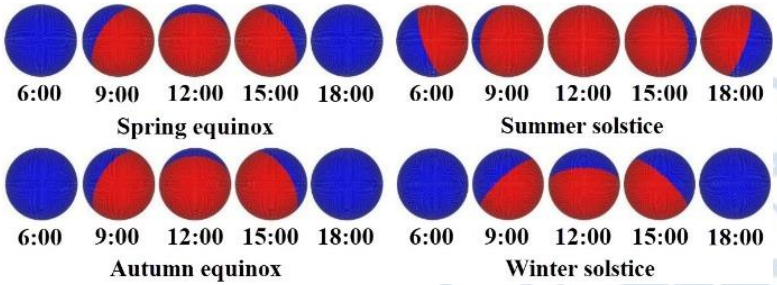


Conversion relationship between OXYZ and oxyz

$$\sin\alpha_s = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\psi$$

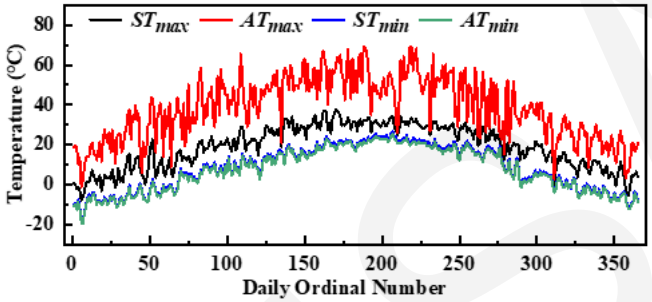
$$\cos\beta_s = \frac{\sin\delta - \sin\alpha_s\sin\phi}{\cos\alpha_s\cos\phi}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos A_s & 0 & -\sin A_s \\ 0 & 1 & 0 \\ \sin A_s & 0 & \cos A_s \end{bmatrix} \cdot \begin{bmatrix} \cos B_s & \sin B_s & 0 \\ -\sin B_s & \cos B_s & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

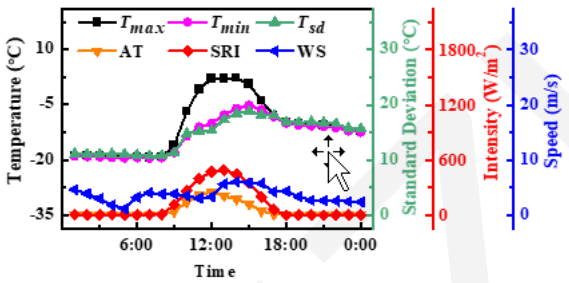


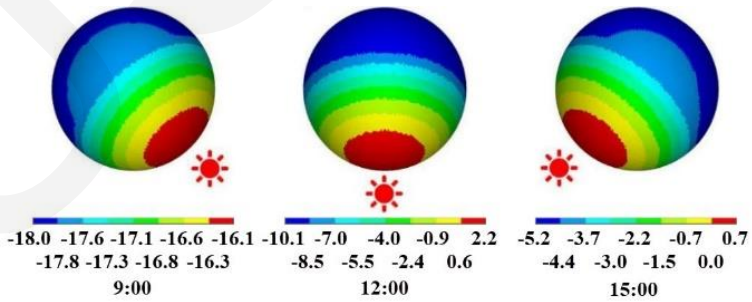
Shadow distribution variation on important solar cycle dates

Analysis of non-uniform temperature field

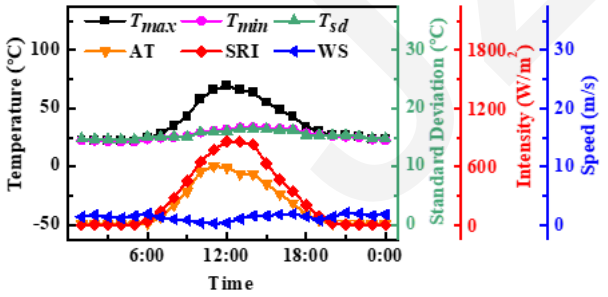


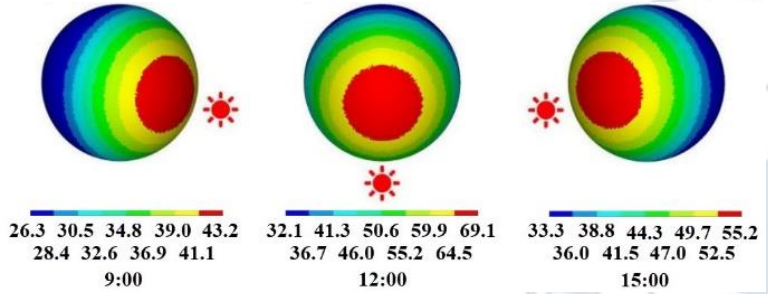
Variation curves of structural and atmospheric temperatures in 2021





Simulated temperature fields on January 7





Simulated temperature fields on July 7

Theoretical derivation

The general form of the transient heat conduction differential equation for a steel plate exposed to the natural environment is expressed as

$$\frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=\frac{\partial T}{\partial t}$$

Addressing the temperature problem requires solving the heat conduction differential equation via initial and boundary conditions. The initial condition defines the steel plate's initial temperature, while the boundary condition outlines the heat exchange at the plate's boundary, as described by:

$$\lambda\frac{\partial T}{\partial n}\bigg|_{\Gamma}=q(t)$$

Due to steel's high thermal conductivity, the temperature gradient across the plate section is negligible, making the heat flux from the interior to the surface zero. Hence, the above equation is expressed as:

$$\lambda\frac{\partial T}{\partial n}\bigg|_{\Gamma}=0$$

On the plate surface, the heat flow loads that contain the heat fluxes of convective heat transfer, solar radiation, and longwave radiation are reflected as

$$q=q_c+q_s+q_l$$

Convective heat transfer between the plate surface and flowing air is computed by

$$q_c=h_c\left(T_a-T\right)$$

Solar radiation absorbed by the plate surface is calculated by

$$q_s=\alpha\left(I_b\omega\cos\theta+I_dF_{ws}+I_tR_gF_{wg}\right)$$

$$\omega=0\ \text{ for }\ \cos\theta\le 0;1\ \text{for}\ \cos\theta>0$$

$$\cos\theta=\cos\alpha_s\cos\gamma\sin\varphi+\sin\alpha_s\cos\varphi$$

$$F_{ws}=0.5\left(1+\cos\varphi\right)$$

$$F_{wg}=0.5\left(1-\cos\varphi\right)$$

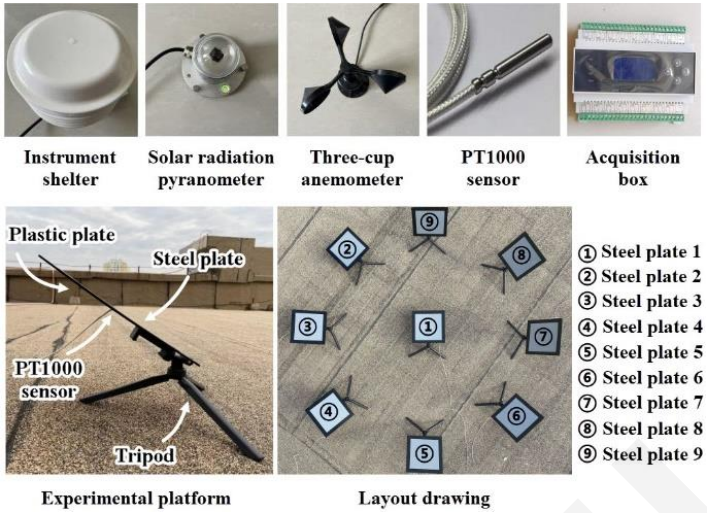
Longwave radiation absorbed by the plate sur-face is calculated by

$$q_l=q_{l,s}+q_{l,g}$$

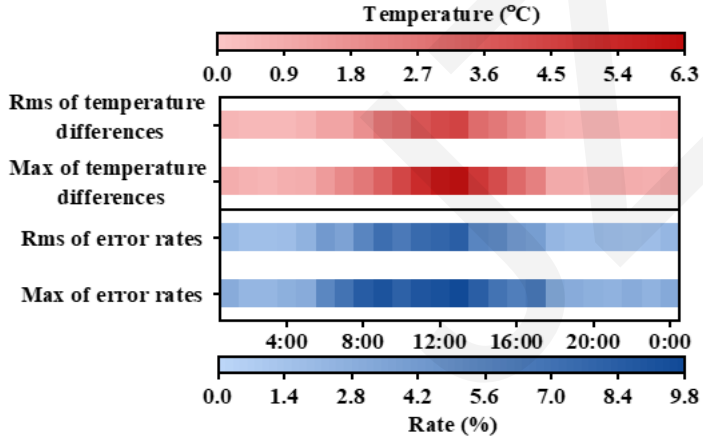
$$q_{l,s}=\varepsilon_f\sigma\left(T_s^4-T^4\right)F_{ws}$$

$$q_{l,g}=\varepsilon_f\sigma\left(T_g^4-T^4\right)F_{wg}$$

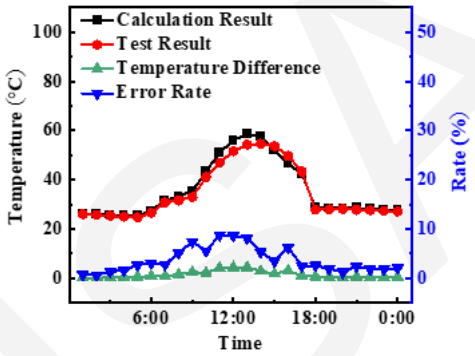
Experimental verification



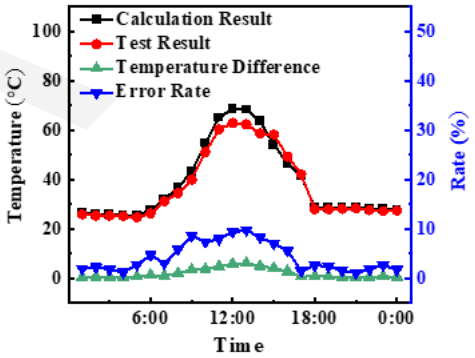
Test equipment and experimental platforms



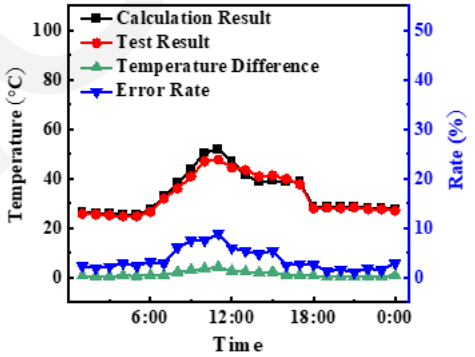
Temperature difference and error rate between measured and calculated results on July 19



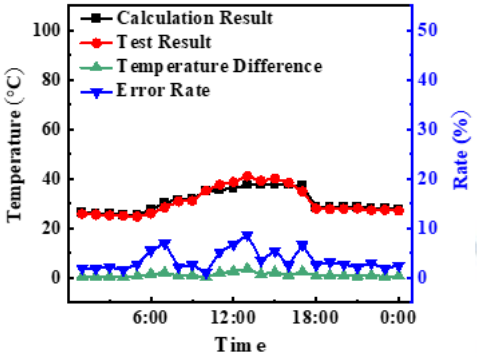
Temperatures of steel plate 3 on July 19



Temperatures of steel plate 5 on July 19

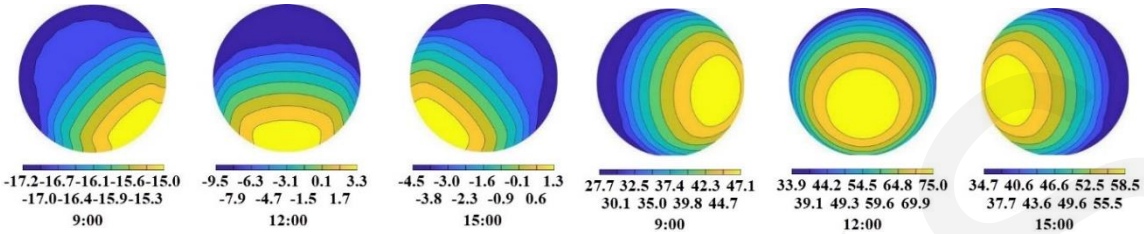


Temperatures of steel plate 7 on July 19



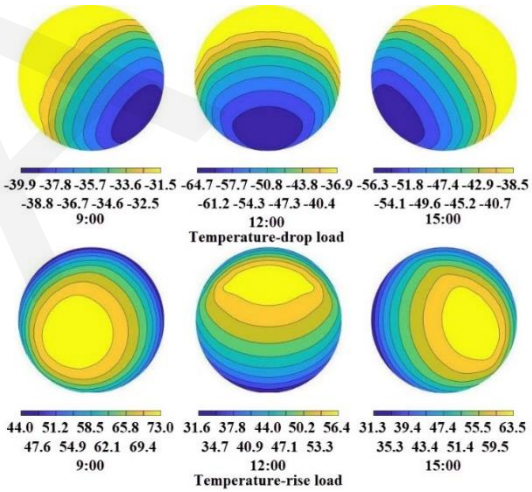
Temperatures of steel plate 9 on July 19

Numerical verification and thermal load design

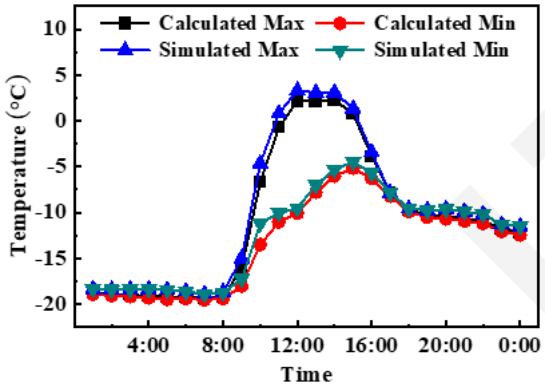


Calculated temperature fields on January 7

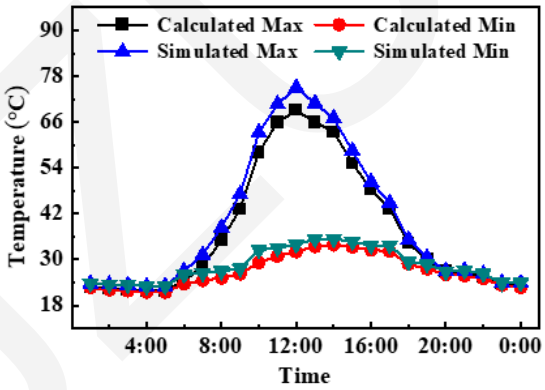
Calculated temperature fields on July 7



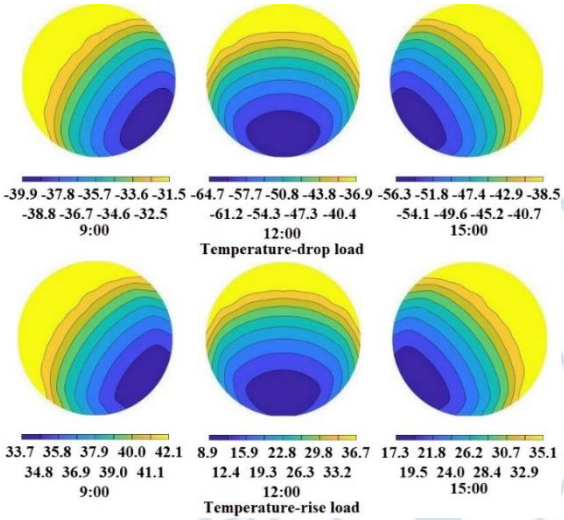
Non-uniform thermal loads for glass roof



Simulated vs calculated results on January 7

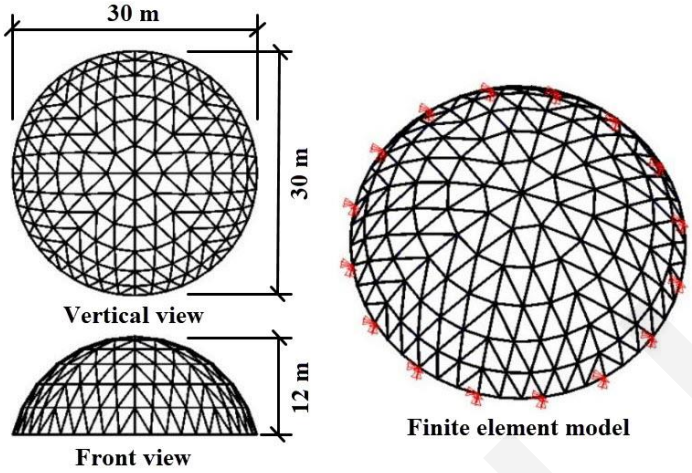


Simulated vs calculated results on July 7

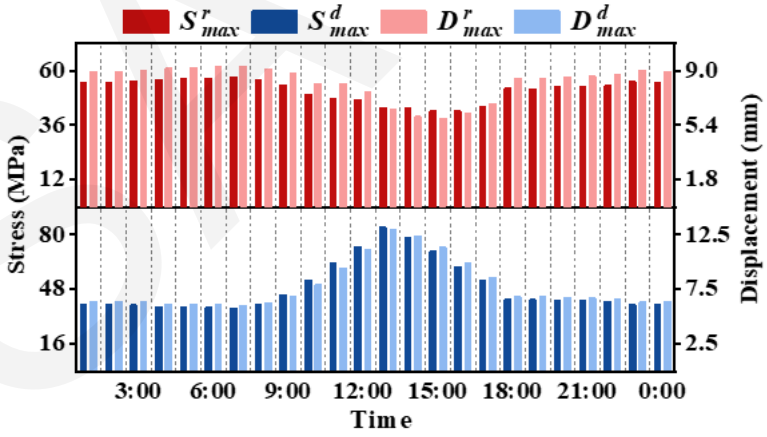


Non-uniform thermal loads for opaque roof

Analysis of non-uniform thermal effect



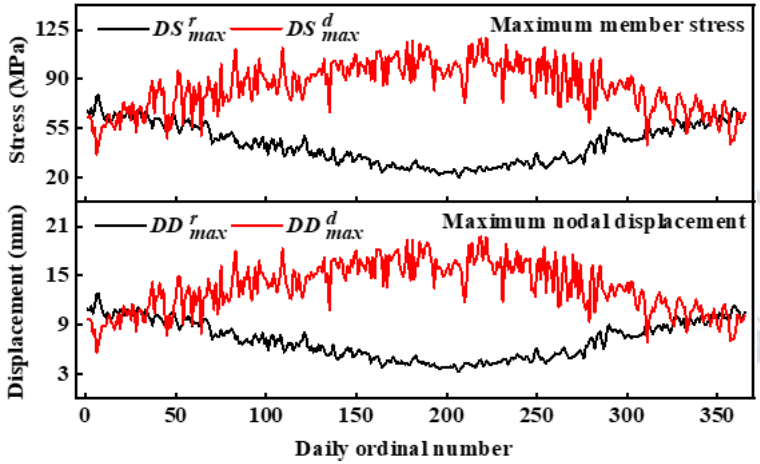
Finite element model for structural analysis



Variation curves of non-uniform thermal effects for healing times on March 1

Uniform and non-uniform thermal effects

Load type	Healing time	Maximum member stress (MPa)	Maximum nodal displacement (mm)
UTRL	\	44.6	7.3
UTDL	\	44.6	7.3
NTRL	9:00, March 1	53.8	8.8
	12:00, March 1	47.1	7.6
	15:00, March 1	42.1	5.8
NTDL	9:00, March 1	44.5	6.8
	12:00, March 1	73.0	11.1
	15:00, March 1	70.1	11.3



Variation curves of non-uniform thermal effects for healing times in 2021

Conclusions

- Using a systematic numerical method and considering practical environmental boundary conditions, shadow variations, and the dynamic coupling effect of environmental factors, long-term temperature changes in a single-layer spherical reticulated shell were simulated. The non-uniform distribution characteristics and time-variant regularity of the structure's temperature field were analyzed from the perspective of seasonal and daily variations.
- By integrating numerical analysis results, a simplified design method for non-uniform thermal loads of single-layer spherical reticulated shells was proposed via theoretical derivation. The method effectively evaluates the impacts of time-varying environmental factors like non-uniform solar and longwave radiations absorption, and convective heat transfer between the structure and flowing air, on the structure's temperature field.
- Verification experiments revealed a maximum temperature difference of 6.1℃ and a maximum error rate 9.7% between the calculated and tested results. The distribution patterns of simulated and calculated temperature fields align, with the deviations not exceeding 6℃. Through comparative analysis, the design method's accuracy and reliability were validated, and its application was demonstrated in several cases.
- The design method was employed to examine non-uniform thermal effects on a single-layer spherical reticulated shell. Under non-uniform thermal loads, the maximum member stress and nodal displacement reach 119.3 MPa and 19.7 mm, respectively, an increase of 167.5% and 169.9% compared to uniform loads. Furthermore, the impacts of healing construction time on non-uniform thermal effects were assessed, leading to construction recommendations.