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Solar radiation properties of common membrane roofs used in building structures

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ABSTRACT

Membrane roofs are widely used building materials, and their solar radiation coefficients significantly affect the thermal environment of the steel structures below them. In this study, the solar radiation coefficients of common membrane roof materials, namely, ethylene tetrafluoroethylene (ETFE), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), thermoplastic olefin (TPO), and polyethylene (PE), were obtained from systematic specimen tests. The temperatures of steel plates below different types of membrane roofs were measured during summer under solar radiation. A numerical simulation method was presented and verified. The following conclusions were drawn from the results of the test and numerical analyses. 1) The ETFE and PE membranes have a high solar radiation transmittance of up to 0.8, which can be effectively modified by printing silver dots and by increasing thickness. 2) The PTFE, PVDF, and TPO membranes have a relatively low solar radiation transmittance below 0.25. 3) The temperature of steel structures below the ETFE and PE membranes is over 61.7 °C during summer, which is at least 27.7 °C higher than ambient air temperature. 4) The temperature of steel structures below the PTFE, PVDF, and TPO membranes is over 41.2 °C during summer, which is at least 7.2 °C higher than ambient air temperature.

1. Introduction

Given their lightness and aesthetically pleasing appearance, membrane roofs have been commonly used in large-span steel structures in recent years [1–3], such as the Eden Project (Fig. 1) in the United Kingdom and the Beijing National Aquatics Center (Fig. 2) in China, among others. However, given the high solar transmittance of these membrane roofs, a considerable amount of solar radiation can pass through them and irradiate on the steel structures below them. Consequently, the temperature of the steel structures becomes significantly higher than the corresponding ambient air temperature, which induces remarkable thermal stress and thermal displacement on the steel structures [4–8]. Therefore, a non-uniform thermal load under solar radiation is the key load for large-span steel structures with membrane roofs.

In some large-span steel structures, the steel members may be set in an enclosed space between the upper membrane roof and the lower membrane ceiling; a good example of such structure is the China National Stadium [9]. In the China National Stadium, the steel members are enclosed by the upper ethylene tetrafluoroethylene (ETFE) membrane roof (with high solar transmittance) and the lower polytetrafluoroethylene (PTFE) membrane ceiling (with low solar transmittance), as shown in Fig. 3. Therefore, a considerable amount of radiant energy can enter the enclosed space through the upper ETFE membrane roof, but only a small amount can pass through the lower PTFE membrane ceiling. As mentioned earlier, a closed warm box is formed, which induces a significant and complicated non-uniform temperature field on the steel members under solar radiation.

Current research on membrane materials has focused on fabrication techniques [10–11], mechanical properties [1,12], thermal properties [2], and design methods [3]. Only a few studies have addressed solar radiation properties, which significantly affect the indoor thermal environment of buildings and the temperature of steel structures below the roof. In addition, several works on thermal indoor environment under membrane roofs have also been conducted in recent years [13–15]. Jiang [16–17] measured and simulated the thermal environment in a built space under a membrane structure. Harris [18] considered the long-wave transmission properties of ETFE materials and explained the necessity for a methodology for estimating surface temperatures, heat losses, and solar gains.

In the present study, the solar radiation properties of membrane roofs with different materials, colors, thickness values, and printing dot ratios were obtained through testing. Furthermore, the temperatures of steel plates under different types of membrane roofs and enclosing conditions were measured during summer. A numerical simulation method using a CFD package was also presented to analyze

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Fig. 1. Eden Project.

the temperature of steel members under membrane roofs, which was verified using the test results. The solar radiation properties of the membrane roofs and their thermal effect on the steel structures below them were discussed based on the experimental and analytical results.

2. Measurement of the solar radiation coefficients of the membrane roofs

2.1. Measurement method

The solar radiation that eventually reaches the surface of the Earth has a wavelength range of 280–2500 nm, mostly from 400 nm to 2000 nm. When sunlight irradiates on an object, the object absorbs, reflects, and transmits solar radiation. The ratios of the absorbed, reflected, and transmitted energy to the total solar radiation are defined as solar absorptance α_s, solar reflectance ρ_s, and solar transmittance τ_s, respectively. The relationship among these three coefficients is described as Eq. (1):

$$\alpha_s + \rho_s + \tau_s = 1. \quad (1)$$

In this study, the spectroscopy method was adopted to measure the solar radiation coefficients. First, the reflectance and transmittance of a membrane roof for each wavelength ranging from 400 nm to 2000 nm were measured using an ultraviolet–visible–near infrared spectrophotometer with an integrated sphere. Then, solar reflectance and solar transmittance were calculated using Eqs. (2) and (3), respectively, whereas solar absorptance was calculated using Eq. (1).

$$\tau_s = \frac{\sum_{i=1}^{n} \tau(\lambda_i) E_s(\lambda_i) \Delta\lambda_i}{\sum_{i=1}^{n} E_s(\lambda_i) \Delta\lambda_i}, \quad (2)$$

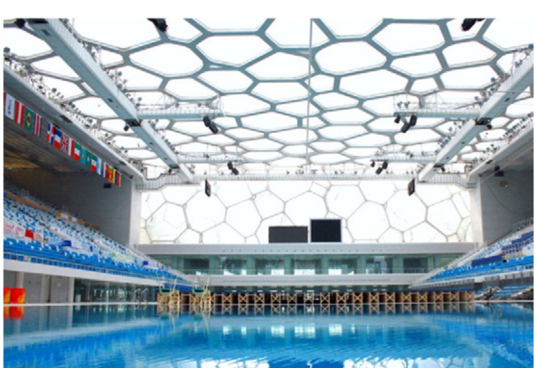

Fig. 2. Beijing National Aquatics Center.

$$\rho_s = \frac{\sum_{i=1}^{n} \rho_0(\lambda_i) \rho(\lambda_i) E_s(\lambda_i) \Delta\lambda_i}{\sum_{i=1}^{n} E_s(\lambda_i) \Delta\lambda_i}, \quad (3)$$

where $\tau(\lambda_i)$ = transmittance of a membrane roof for the optical spectrum at wavelength λ_i; $E_s(\lambda_i)$ = spectral intensity of the optical spectrum at wavelength λ_i; $\Delta\lambda_i$ = wavelength interval, and $\Delta\lambda_i = (\lambda_{i+1} - \lambda_{i-1})/2$; n = number of measuring points; $\rho_0(\lambda_i)$ = reflectance of the standard whiteboard for the optical spectrum at wavelength λ_i; $\rho(\lambda_i)$ = reflectance of a membrane relative to the standard whiteboard for the optical spectrum at wavelength λ_i.

Solar radiation spectral intensity and wavelength interval were determined from the Code ASTM G173-03.

2.2. Specimen design

Five types of membranes, which are typically used as building roofs, were selected to obtain their solar radiation coefficients. These membranes were ETFE, PTFE, polyvinyl chloride (PVC) with polyvinylidene fluoride (PVDF) coating, thermoplastic olefin (TPO), and polyethylene (PE). Considering the effect of thickness, printing silver dot ratio, and surface color, 25 membrane specimens were designed in this research. Then, 3 of the same specimens for each membrane were manufactured and measured. The average value was considered for the final result.

For the ETFE membrane, 11 specimens were designed with different colors, printing silver dot ratios, and layer numbers (Fig. 5 and Table 1). For the PTFE membrane, the color was brown after manufacturing, and then turned into white after 3 months under solar radiation. Considering the color changes and the different manufacturers, 11 specimens of the PTFE membrane were designed (Fig. 4 and Table 1). The FGT specimens were from SKYTOP PTFE. The B18039 and B18089 specimens were from the Duraskin Membrane Company in Germany. The H302 specimen was from the Weilikai Membrane Company in China. For the PVC–PVDF, TPO, and PE membranes, one specimen from each kind was designed in this research, as listed in Fig. 4 and Table 1.

2.3. Analysis of the results

The solar absorptance α_s, solar reflectance ρ_s, and solar transmittance τ_s, of all the specimens are listed in Table 1. These variables provide a significant parameter value in the non-uniform temperature numerical simulation model for steel structures below a membrane roof under solar radiation. The transmittance and reflectance curves within the wavelength range of 400–2000 nm for all the specimens are shown in Figs. 5 and 6, respectively.

The following conclusions were drawn from Table 1 and Figs. 5 to 6.

(1) The solar radiation transmittance of the ETFE membrane without printing dots and the PE membrane is higher than that of the other types of membranes. The solar radiation transmittance of the PTFE and PVDF membranes is lower, whereas that of the TPO membrane is the lowest, with a value of 0. The colorless single-layer ETFE membrane without printing dots has the highest solar radiation transmittance, with a value of 0.8.
(2) The printing dot in the ETFE membrane has a weak solar radiation transmittance but strong reflectance and absorptance; thus, the solar radiation transmittance of the ETFE membrane is modified by arranging different printing dot ratios, which is validated by the test results in Table 1. For example, the solar radiation transmittance values of the ETFE membrane with printing dot ratios of 0%, 63%, and 80% are 0.8, 0.32, and 0.16, respectively.
(3) The solar radiation transmittance of the ETFE membrane decreases with layer number, which is validated by the test results in Table 1. For example, the solar radiation transmittance values