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Wind pressure distribution on the open membrane structure

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ABSTRACT

There are challenges in measuring the peak net wind pressures on membrane structures with the outstanding opening due to thinness of the membrane. In this study, wind tunnel tests were conducted on a case study membrane structure in Gwangju Sajik Park. Wind pressures on the upper and lower surfaces were measured separately, and a technique to combine these measurements for peak net wind pressure estimation was proposed. In addition, the test results were compared with peak wind pressure coefficients for dome structures in KDS 41 12 00:2022.

1. INTRODUCTION

Membrane structures are commonly used in facilities such as sports arenas or concert venues. Korean Design Code (KDS 41 12 00:2022) provides external wind pressure coefficients of dome structures, which were presented with an assumption that the underside of dome structure is enclosed. Thus, they are not applicable to most membrane structures where the underside is open. In such cases, KDS 41 12 00:2022 stipulates that wind pressure should be determined through wind pressure tests.

Although wind pressure tests are used to determine wind loads on structures, there are several challenges in wind tunnel tests of open membrane structures. Due to the thinness of membrane structures, it is difficult to conceal the essential wind pressure tubes within the test models. If pressure tubes are exposed externally, the airflow near the surface may be affected, resulting in inaccurate experimental results. To avoid such problem, Sun et al. (2020) and Kandel et al. (2022) conducted tests on two types of models. One model had an enclosed lower section, and the other model

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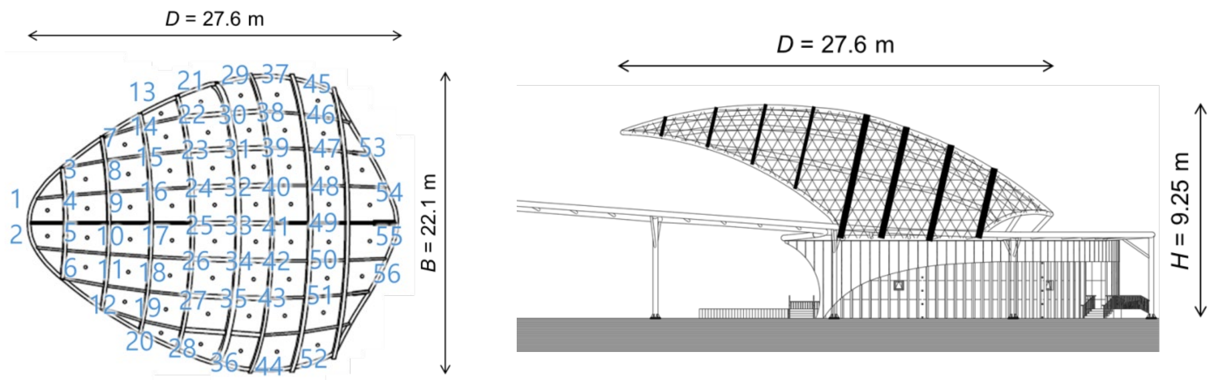
had a thickened membrane with tubes concealed inside the structure. In the latter case, it may be difficult to fabricate models with irregular shapes. In addition, there is a high possibility that tubes may bend excessively and become blocked due to the thickness of membrane. On the other hand, Ko et al. (2008) measured wind pressures on upper and lower surfaces separately. The limitation of such method is that pressures on the upper and lower surfaces cannot be measured simultaneously, which results in challenges on the determination of peak net pressure.

In this study, wind tunnel tests were conducted to measure pressures on upper and lower surface of the case study building separately. A technique was presented to determine the net wind pressure by combining the two results. These results were compared with wind pressure coefficients presented in KDS 41 12 00:2022.

2. CASE STUDY STRUCTURE AND TEST SETUP

The case study building shown in Fig.1 is the membrane structure of concert venue in Gwangju Sajik Park. The structural plan with arrangement of pressure holes and elevation are shown in Fig. 2.

Fig. 1 Membrane structure of Gwangju Sajik Park



(a) Plan and pressure hole arrangement

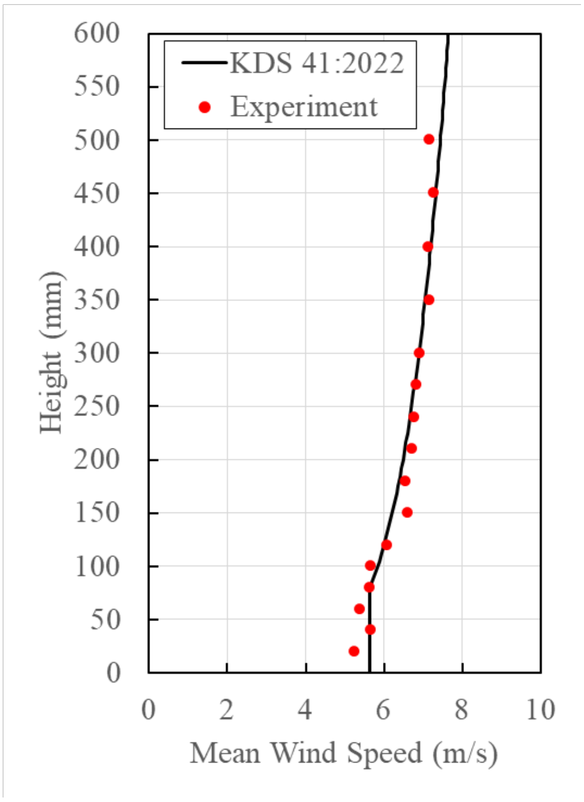
(b) Elevation

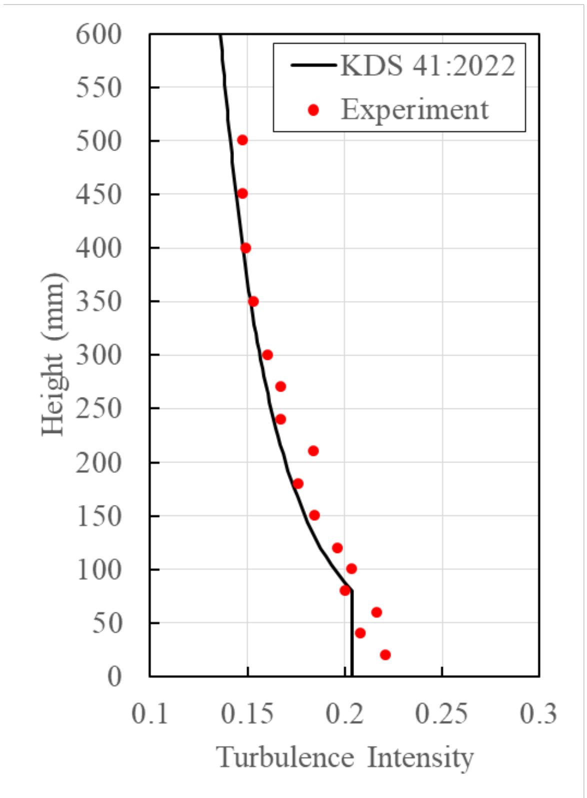
Fig. 2 Plan and elevation of case study structure

Wind tunnel test was carried out in the boundary layer wind tunnel test facility of GEST ENG. The test conditions are summarized in Table 1. The setup of mean wind speed and turbulence intensity profiles is shown in Fig. 3.

Table 1 Test conditions

	Contents	Notes
Length scale	1/125	Model length/structure length
Basic wind speed, V_0	28 m/s	KDS 41 12 00:2022
Importance factor, I_W	0.95	
Roughness Category	C	
Design wind speed, V_H	26.6 m/s	
Test wind speed	5.63 m/s	
Wind speed scale	1/4.72	Test wind speed/ design wind speed
Time scale	1/26.47	Length scale/ wind speed scale
Sampling frequency	700 Hz	
Number of ensembles	5	



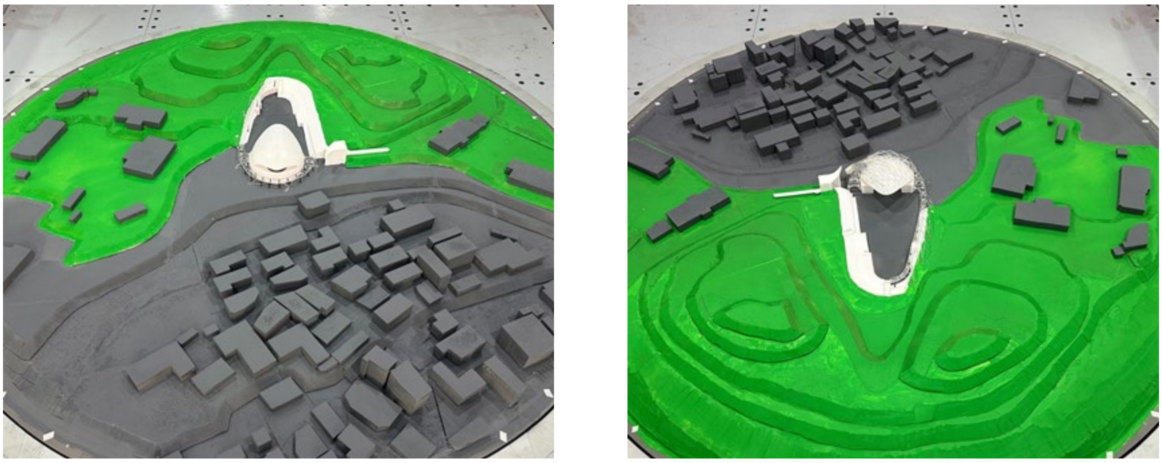


(a) Mean wind speed (b) Turbulence intensity

Fig. 3 Mean wind speed and turbulence intensity profiles

3. COMBINATION OF SEPARATELY MEASURED DATA

The pressures on upper and lower surfaces were measured using different test models as shown in Fig. 4.



(a) Upper surface measurement model (b) Lower surface measurement model
Fig. 4 Wind tunnel test models

Because the tests were not conducted simultaneously, the maximum net pressure cannot be directly obtained. The probability of occurrence of maximum pressures of upper and lower surfaces at the same time is low. Calculating the maximum net pressure as difference of the two maximum pressures may be too conservative. In this case, the concept of wind load combination can be used.

In the studies by Jeong and Kang (2022), the correlation coefficient of two time histories of *X* and *Y* can be expressed as the follows.

$$\rho = \sum_{i=1}^{n} \sqrt{\frac{S_X(f_i)\Delta f}{\int_0^\infty S_X(f)df} \cdot \frac{S_Y(f_i)\Delta f}{\int_0^\infty S_Y(f)df}} \cos(\theta_{Xi} - \theta_{Yi}) \tag{1}$$

Where $S(f)$ is one-sided power spectral density (PSD), f is frequency, and θ is phase angle. The maximum value of correlation coefficient is limited by the similarity of PSDs as the follows.

$$\rho_{\max} = \sum_{i=1}^{n} \sqrt{\frac{S_X(f_i)\Delta f}{\int_0^\infty S_X(f)df} \cdot \frac{S_Y(f_i)\Delta f}{\int_0^\infty S_Y(f)df}} \tag{2}$$

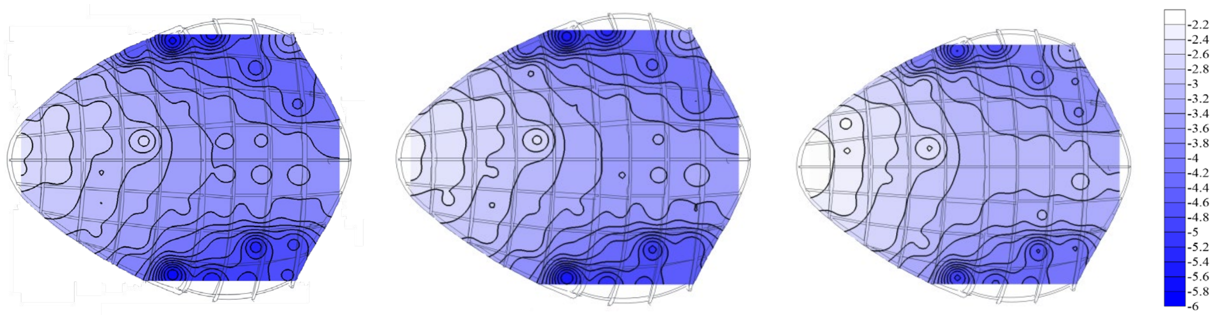
Thus, even if the exact correlation coefficient cannot be determined due to limitation of measurement method, the maximum possible correlation coefficient of the two time histories ca be conservatively estimated using Equation (2).

The load combination factor (κ) can be conservatively determined using the correlation coefficient (AIJ, 2019).

$$\kappa = \sqrt{2+2\rho} - 1 \tag{3}$$

Although the correlation coefficient is zero, the minimum value of load combination factor is about 0.4.

The peak net wind pressure coefficients using the following three methods were compared in Fig. 5. Because the design wind load was governed by the negative peak net pressure, only the negative case is shown in Fig. 5. The first method, which is the most conservative, assumed correlation coefficients of 1 for all locations. The peak net wind pressure was determined as the difference between the maximum values on the upper and lower surface. The second method was using load combination factors based on Equation (2). The third method assumed correlation coefficients of 0 for all locations. For net pressure coefficients, the positive value is direction from the upper surface to the lower surface. The results are summarized in Table 2.



(a) Method 1 (b) Method 2 (c) Method 3

Fig. 5 Peak net wind pressure coefficients

Table 2 Comparison of peak net wind pressure coefficients

	Method 1 (Full correlation)	Method 2 (Eq. (2))	Method 3 (No correlation)
$C'_{p,net,max}$ (Hole No.)	2.9375 (No. 2)	2.7735 (No. 2)	2.4619 (No. 2)
$C'_{p,net,min}$ (Hole No.)	-5.9581 (No. 28)	-5.7939 (No. 28)	-5.2469 (No. 28)

The difference between full correlation method and no correlation method was about 12%. Using the equation (2), the difference with the full correlation method reduced to 3%.

KDS 41 12 00:2022 provides peak external pressure coefficients ($C'_{p,e}$) for circular-shaped dome roof structure. Although the coefficients are for the enclosed structure as shown in Fig. 6, the peak external pressure coefficients for case study structure were calculated. The peak internal pressure coefficient ($C'_{p,i}$) for partially closed structure with an outstanding opening is given as ±1.40 in KDS. The peak net pressure coefficients based on KDS are summarized in Table 3.

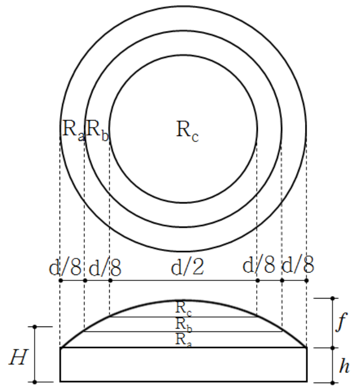


Fig. 6 Parameters for determination of peak external pressure coefficients of the dome roof structure in KDS 41 12 00:2022

Table 3 Peak net wind pressure coefficients based on KDS 41 12 00:2022

Location	R_a	R_b	R_c
$C'_{p,e,positive}$	1.3224	1.0247	0.1865
$C'_{p,e,negative}$	-2.2200	-2.2300	-2.4300
$C'_{p,i}$		±1.40	
$C'_{p,net,max}$	2.7224	2.4247	1.5865
$C'_{p,net,min}$	-3.6200	-3.6300	-3.8300

The negative peak net pressure coefficients by KDS were much lower than test results. It is due to an inaccurate and rough estimation of internal pressure of open structure. Additionally, the wind pressure distribution varied with the inclination angle of the structure, showing significant differences, especially at the edges of the membrane structure.

4. CONCLUSION

In this study, wind tunnel tests of the membrane structure were conducted. The pressures of upper and lower surfaces were measured separately, and the calculation methods of peak net pressure coefficients were studied. A method to consider correlation coefficients of pressures on the two surfaces using PSD similarity (Method 2) was proposed. It is a conservative approach to consider the maximum limit of correlation coefficients depending on the PSD similarity. Using the proposed method, an optimized design compared with fully correlated method (Method 1) can be achieved.

In addition, test results were compared with peak pressure coefficients by KDS 41 12 00:2022. Due to the inaccurate estimation of internal pressure in KDS, peak net pressure coefficients were underestimated. For a membrane structure with outstanding opening, the estimation of wind loads based on wind tunnel test is recommended.

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