DETERMINATION OF WIND LOADS ON POROUS SUNSHADE ROOF COVER SHEETS USING CONVERSION FACTOR

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Abstract: *Porous sunshade roof cover sheets installed on building roofs are new structures for mitigating heat absorption. Thus, there have been few studies on wind flow and its effects on wind-permeable structures, and there is no provision for these structures in the major international wind load standards and codes. Unlike wind loading on building roofs, wind loading on porous sunshade roof cover sheets is a combination of wind pressures on both the upper and lower surfaces, which complicates the calculation of wind loading. From the viewpoint of structural design, we need a simple method for determining wind loading on these structures. Wind tunnel tests have been carried out for various wind angles, three porosities (ratio between area of orifices and area of sheet), and five gaps between sheet and roof, and results have been analyzed. As a result, the author proposes a simple formula for calculating wind loading on porous sunshade roof cover sheets from wind loadings on normal building roofs available from wind loading codes and standards. The calculated results based on this formula and the Japanese wind loading standard (AIJ-RFLB (2015))[4] are compared with those of wind tunnel tests. There is a good similarity between them.*

Keywords: *conversion factor, wind loading, porous sunshade roof cover sheet, low-rise building, wind tunnel test*

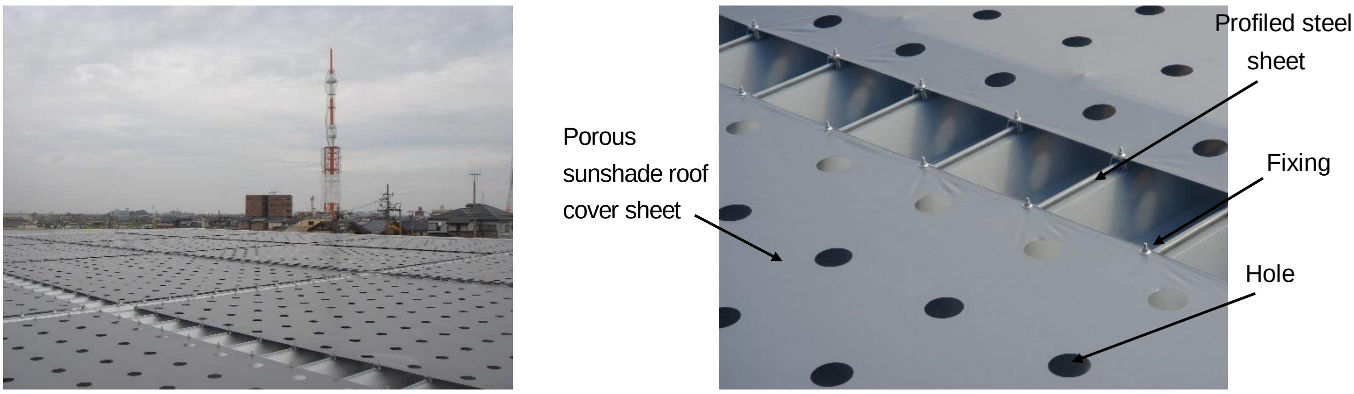
1. Introduction

Thermal reduction is always a problem for building roofing systems, especially profiled steel sheet systems. It reduces requirements for heating and cooling system capacities, increases occupant comfort, and even eliminates condensation on roof surfaces in cold climates. Up to now, there are several solutions for roof insulation such as loose laid paver system, heat insulation roof tile and so forth. But the cost of these solutions is still expensive. Porous sunshade roof cover sheets have been introduced to be a new solution. Fig. 1 shows some pictures of application of the porous sunshade roof cover sheets for a real roof of low-rise building. There was some research on wind loads on porous roofs or wind-permeable facades [1-3]. Wind loading on this type of structure depends on the difference between the pressures on the upper and lower surfaces. It is therefore important to be able to assess the influences of porosity and underneath volume ratio on wind loading on these sheets. This paper proposes a new formula to determine wind loading on porous sunshade roof cover sheets.

2. Test set-up

A low-rise building model (200 mm high (H) $\times$ 470 mm wide (B) $\times$ 710 mm deep (D)) with porous sunshade roof cover sheets was tested in a Boundary Layer Wind Tunnel, located at Tokyo Polytechnic University, Japan. The length and velocity scales were 1/50 and 1/4, respectively. Terrain category III (power law index of 0.2) in [4] was chosen for the tests. The turbulence intensity at height 200 mm (10 m in full scale) was 0.26 and the wind speed was 7m/s. Fig. 2 shows mean wind speed and turbulence intensity profiles. There were 3 test model cases to consider the effect of porosities (ratio between area of orifices and area of the sheet) of the porous sunshade roof cover sheets (0%, 5% and 10%) with the gap between the sheet and the profiled roof a = 4.7 mm (corresponding to underneath volume ratios $V^* = a/(a+H)$ = 0.018) (see Fig. 3). And there were 5 test model cases (porosity ϕ = 5%) to consider the effect of underneath volume. The underneath volume was modified by adjusting gap between the sheet and the folded roof, a, (see Fig. 3(d)). The values of a = 4.7, 5.7, 6.7, 8.7 and 10.7 mm for the folded roof corresponding to gaps between the sheet respectively. They created underneath volume ratios $V^* = a/(a+H)$ = 0.018, 0.023, 0.027, 0.037 and 0.046 respectively. The model had sixteen porous sunshade roof cover sheets, one with 128 holes, while four porous sunshade roof cover sheets had pressure taps (A, B, C and D) (see Fig. 3).

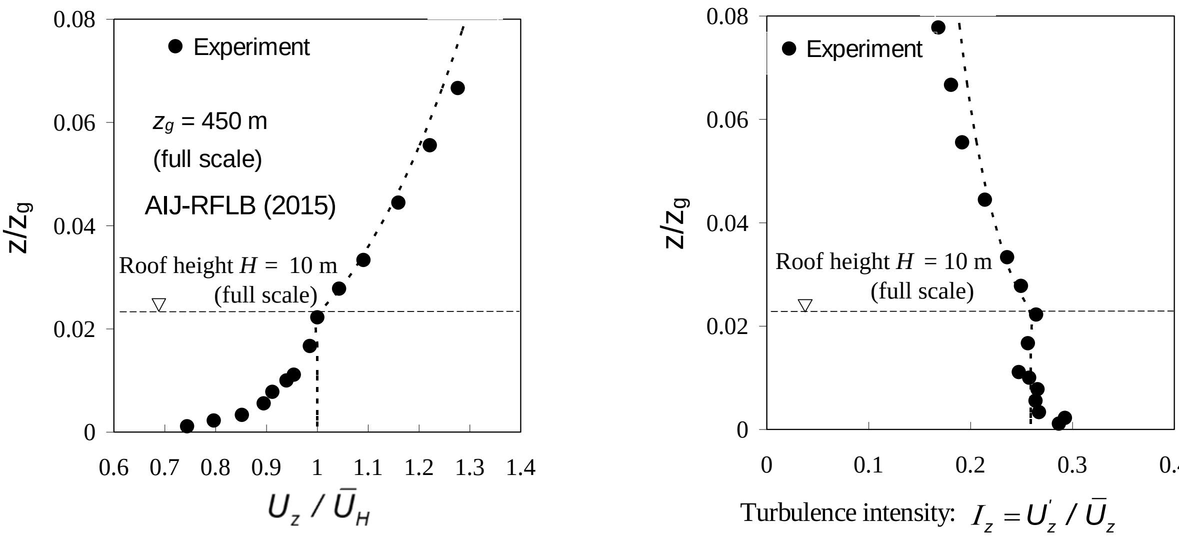
All test model cases were tested with a total of 41 wind angles (0º to 360º in 10º steps and four wind angles: 45º, 135º, 225º and 315º).



(a) A real arrangement of porous sunshade roof cover sheets on a low-rise building

(b) Close-up view of a porous sunshade roof cover sheet

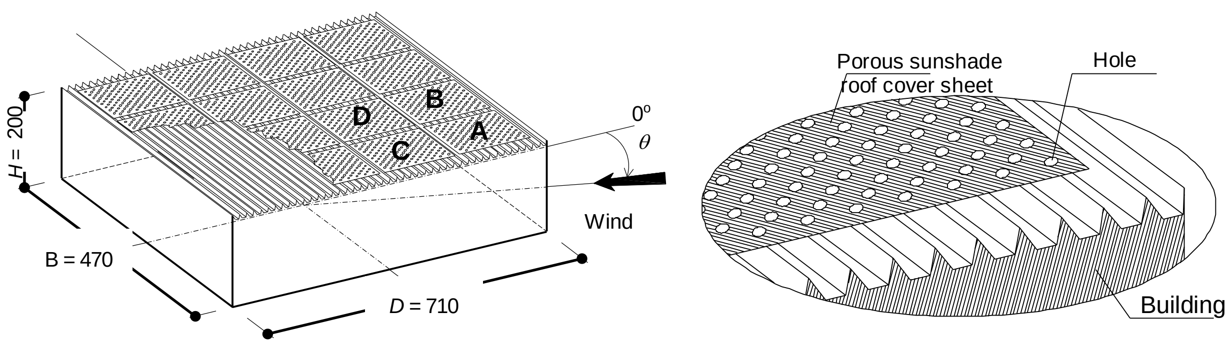
Fig. 1. *Pictures of application of porous sunshade roof cover sheet*



(a) Mean wind speed profile

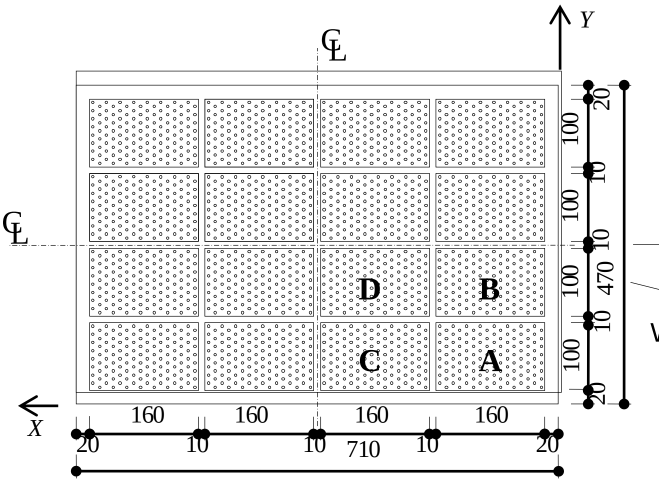
(b) Turbulence intensity profile

Fig. 2. *Simulated wind conditions in wind tunnel*

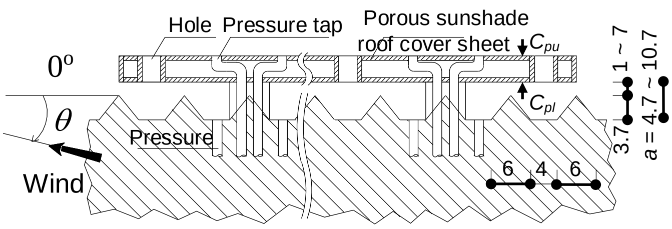


(a) Geometry of test model

(b) Close-up view of a porous sunshade roof cover sheet



(c) Arrangement plan of porous sunshade roof cover sheets

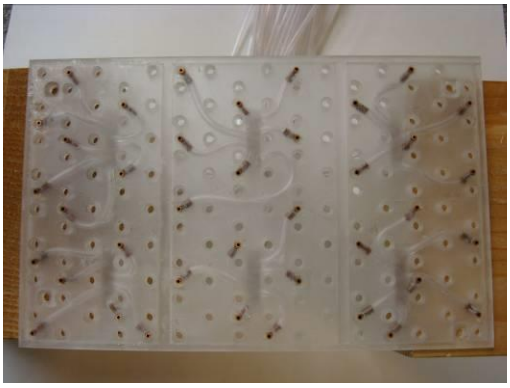


(d) Detail of roof section

Fig. 3. *Test model (all dimensions in mm)*

Fig. 4. shows some pictures of a test model: test model in wind tunnel and a close-up view of a porous sunshade roof cover sheet.

(a) Test model in wind tunnel



(b) Close-up view of a porous sunshade roof cover sheet model

Fig. 4. *Pictures of test model*

3. Results and discussion

3.1 Local wind force coefficient

The local wind force coefficient on the sheet due to the combined effect of the upper and lower surface pressures is

$$C_n(i,t) = C_{pu}(i,t) - C_{pl}(i,t) \tag{1}$$

where $C_{pu}(i,t)$ and $C_{pl}(i,t)$ are wind pressure coefficients at measurement tap i at time t on the upper and lower surfaces of the sheet, respectively; and $C_n(i,t)$ is the local wind force coefficient at measurement tap i at time t of the sheet.

The local wind force coefficients were defined as positive in the vertically downward direction.

3.2 Local reduction factor

The local reduction factor γ_L^{ϕ} for different porosities ϕ was introduced to provide a good view of reduction rate when comparing wind loading on the porous sunshade roof cover sheet with that on the building roof. The local reduction factor γ_L^{ϕ} is defined by:

$$\gamma_L^{\phi} = \frac{\check{C}_n}{\check{C}_{pu}} \tag{2}$$

where $\check{C}_n$ is minimum peak local wind force coefficient; and $\check{C}_{pu}$ is minimum peak upper surface wind pressure coefficient.

The simultaneous local reduction factor γ_L^{ϕ} analyses for all pressure taps for different wind angles are shown for porosities 0%, 5% and 10% respectively from Fig. 5.

The ensemble average values of local reduction factor γ_L^{ϕ} are marked as (•) and the upper and lower values are the standard deviation (—) from the ensemble average values. For porosity ϕ = 0%, Fig. 5 shows that there is a gradual fluctuation in ensemble average values from 0.34 to 0.54. Similarly, ensemble average values varied from 0.27 to 0.43 and from 0.22 to 0.38 for porosities 5% and 10%, respectively. Furthermore, values of standard deviation of γ_L^{ϕ} of porosity ϕ = 0% were 0.08~0.16. These values were 0.05~0.15 and 0.04~0.14 for porosities 5% and 10%. It means that ensemble average values and their standard deviations of γ_L^{ϕ} decrease with increasing porosity.

The local reduction factor γ_L^{V} for different underneath volume ratios V^* and porosity ϕ = 5% is defined as same as γ_L^{ϕ} in Eq. 2.

For underneath volume ratios V^* **=** 0.018, Fig. 6 shows that there is a gradual fluctuation in ensemble average values from 0.27 to 0.43. Similarly, ensemble average values varied from 0.28 to 0.44, from 0.29 to 0.47, from 0.31 to 0.51 and from 0.33 to 0.52 for underneath volume ratios V^* = 0.023, 0.027, 0.037 and 0.046, respectively. Furthermore, values of standard deviation of γ_L^{V} were from 0.05 to 0.14, from 0.05 to 0.15, from 0.05 to 0.15, from 0.07 to 0.20 and from 0.07 to 0.21 for underneath volume ratios V^* = 0.018, 0.023, 0.027, 0.037 and 0.046, respectively. It means that ensemble average values and their standard deviations of γ_L^{V} increase with increasing underneath volume ratio V^*.

From results shown in Fig. 5, we can get values of γ_L^{ϕ} with probability of exceeding 2% to be 0.75, 0.62 and 0.55 for 0%, 5% and 10%, respectively (see Fig. 7). It indicates that local reduction factor γ_L^{ϕ} with probability of exceeding 2% decrease with increasing porosity.

From the results shown in Fig. 6, we can get values of γ_L^{V} with probability of exceeding 2% to be 0.65, 0.66, 0.69, 0.75 and 0.78 underneath volume ratios V^* = 0.018, 0.023, 0.027, 0.037 and 0.046, respectively (see Fig. 8). It indicates that local reduction factor γ_L^{V} with probability of exceeding 2% increase with increasing underneath volume ratio.

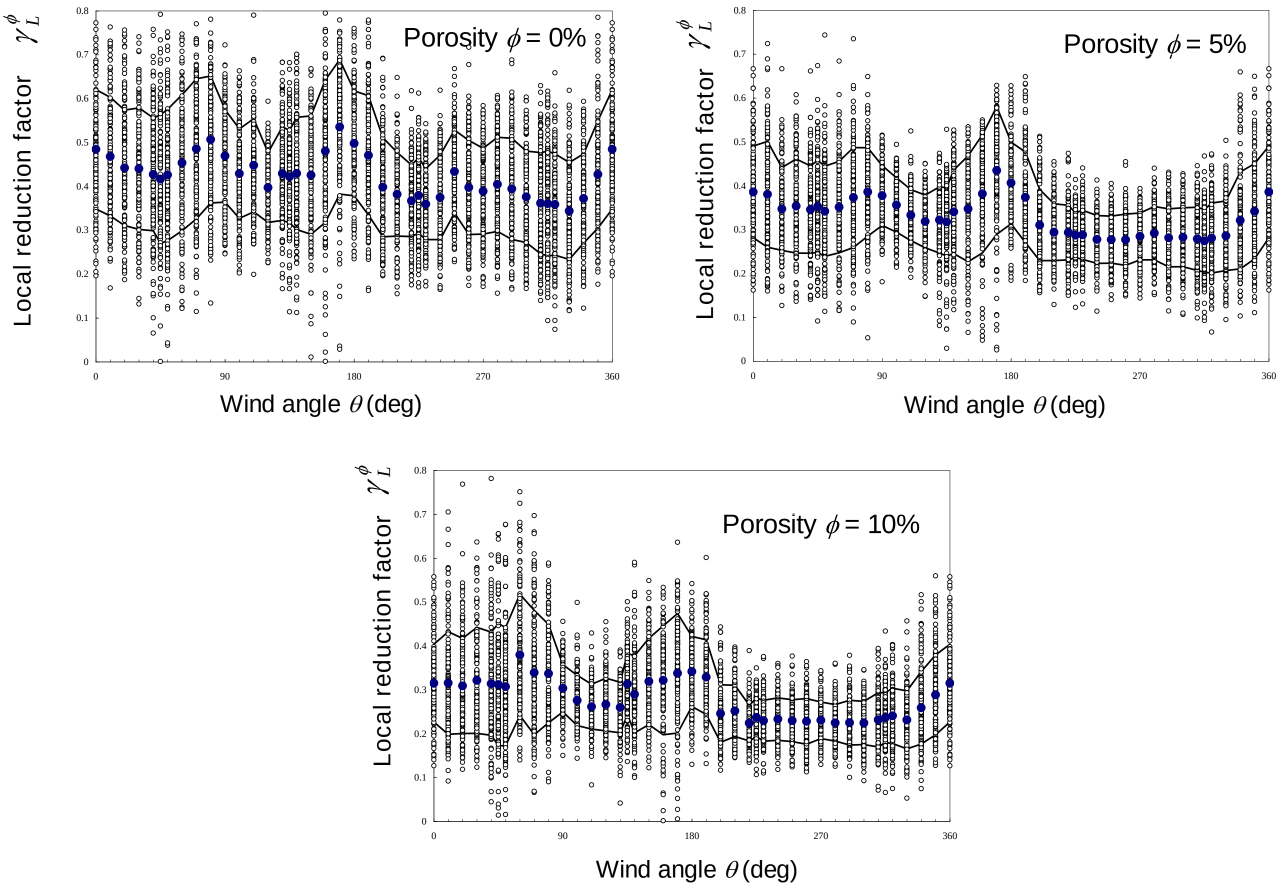


Fig. 5. *Variations of local reduction factor γ_L^{ϕ} with wind angle θ for different porosities ϕ*

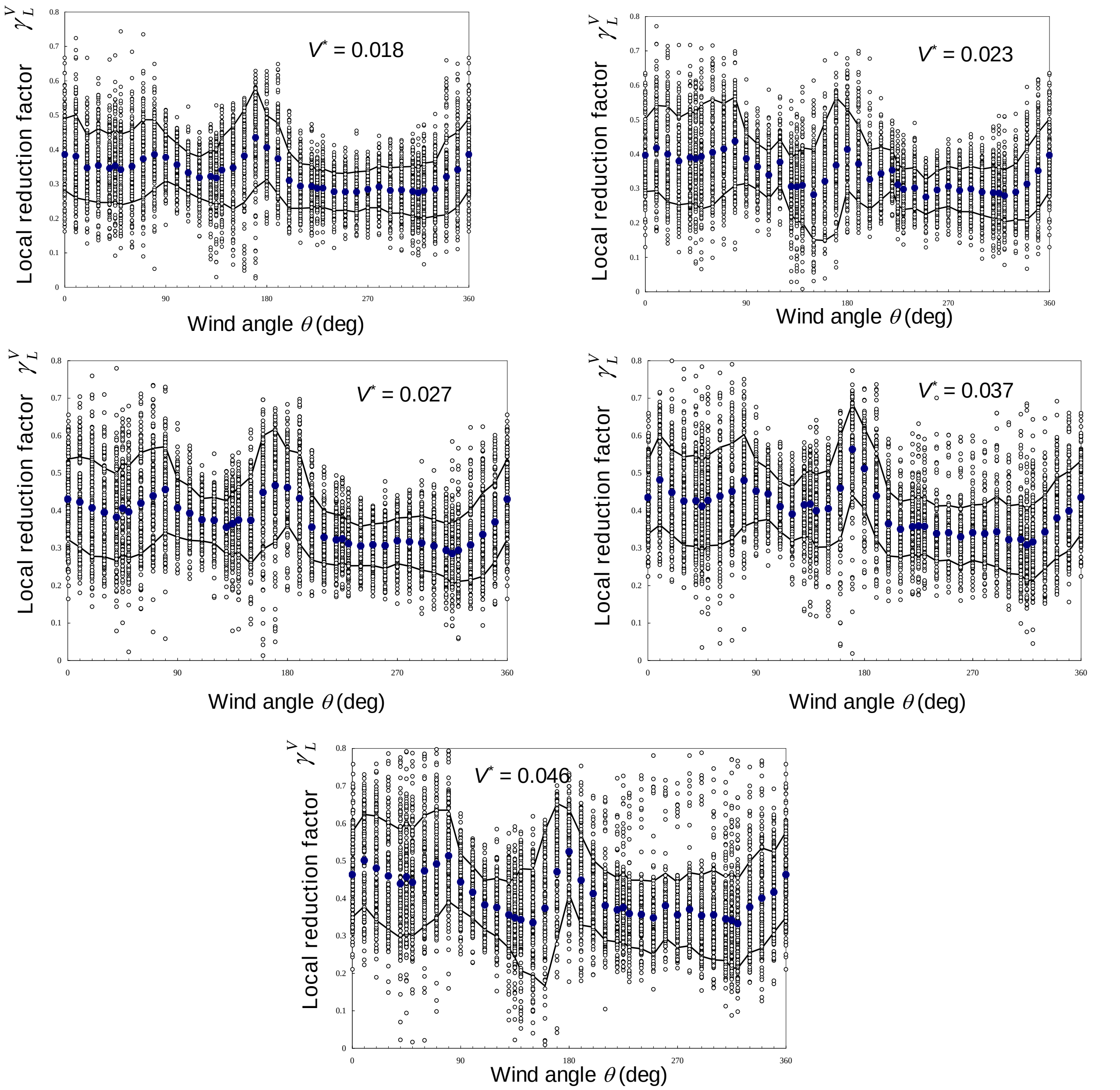


Fig. 6. *Variations of local reduction factor γ_L^V with wind angle θ for different underneath volume ratios V^* for folded roof*

3.3 Conversion factor

Porosity and underneath volume ratio (i.e. gap between sheet and building roof) are two important factors to be considered when determining wind loading on porous sunshade roof cover sheets. From the viewpoint of structural design, we need a simple way (i.e. a simple equation) to determine the wind loading on the sheet based on wind loading determined from [4] and porosity and underneath volume ratio of the sheet. Here, conversion factor for the sheet with porosity ϕ and underneath volume ratio V^* is defined as follows

$$\gamma = \frac{\check{C}_n}{\check{C}_r} \tag{3}$$

where $\check{C}_n$ is minimum peak local wind force coefficient for a porous sunshade roof cover sheet; and $\check{C}_r$ is minimum peak wind pressure coefficient for a normal building roof.

From Eq. 3, minimum peak local wind force coefficient for a porous sunshade roof cover sheet is determined as follows.

$$\check{C}_n = \gamma \check{C}_r \tag{4}$$

Minimum peak wind pressure coefficient for a normal building roof ($\check{C}_r$) can be determined from [4], namely negative peak external pressure coefficient.

The local wind force coefficients for porous sunshade roof cover sheets are very similar to wind pressure coefficients on the normal building roof ($\check{C}_r \approx \check{C}_{pu}$). It means that conversion factor can be determined as follows:

$$\gamma = \frac{\check{C}_n}{\check{C}_{pu}} \qquad (5)$$

where $\check{C}_{pu}$ is minimum peak upper surface wind pressure coefficient.

Conversion factors (local reduction factors) γ_L^{ϕ} for porosity ϕ and an underneath volume ratio V^* = 0.018 are given in Table 1 and Fig. 7.

Table 1. *Conversion factors γ_L^{ϕ} for different porosities ϕ and an underneath volume ratio V^* = 0.018*

Porosity ϕ	0%	5%	10%
γ_L^{ϕ}	0.75	0.62	0.55

Based on data shown in Table 1 and Fig. 7, a function of γ_L^{ϕ} for porous sunshade roof cover sheet was fitted as follows.

$$\gamma_L^{\phi} = -2\phi + 0.74 \qquad (6)$$

Furthermore, conversion factors (local reduction factors) γ_L^{V} for different underneath volume ratios and a porosity ϕ =5% are given in Table 2 and Fig. 8.

Table 2. *Conversion factors γ_L^{V} for different underneath volume ratios V^* and a porosity ϕ = 5%*

Underneath volume ratio V^*	0.018	0.023	0.027	0.037	0.046
γ_L^{V}	0.65	0.67	0.72	0.78	0.8

Based on data shown in Table 2 and Fig. 8, a function of γ_L^{V} for porous sunshade roof cover sheet was fitted as follows.

$$\gamma_L^{V} = 5.8V^* + 0.55 \qquad (7)$$

As already mentioned earlier, Eq. 6 is used for cases that have an underneath volume ratio V^* = 0.018 and different porosities ϕ, whereas Eq. 7 is used for cases have a porosity ϕ = 0.05 and different underneath volume ratios V^*. Therefore, it is difficult to apply these equations to other cases. It needs to have an equation of conversion factor γ depending on porosity ϕ and underneath volume ratio V^*.

Combining two equations (6 and 7), we have the following equation:

$$\gamma = -2\phi + 6.4V^* + 0.62 \qquad (8)$$

Conversion factor γ determined from Eq. 8 can be applied for the sheet with different porosities ϕ and underneath volume ratios V^*. It should be noted that Eq. 8 is only valid for porosity ϕ in the range of 0% ~ 10% and underneath volume ratio V^* in the range of 0.018 ~ 0.046.

Based on Table A6.18 (1) of [4], plan of calculation zone of roof is shown in Fig. 9.

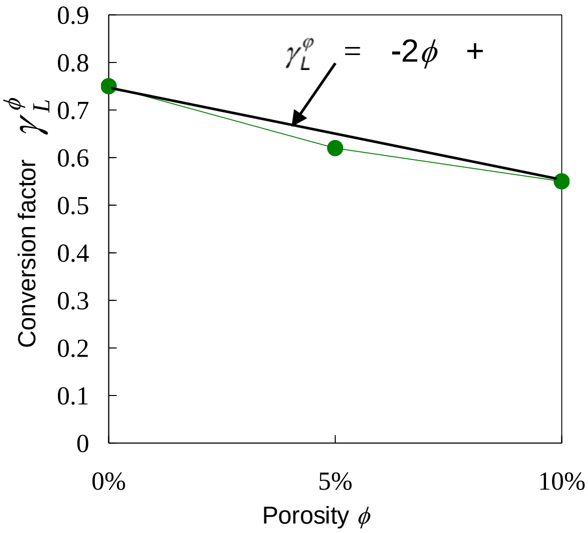


Fig. 7. *Variation of local reduction factor γ_L^{ϕ} with probability of exceeding 2% for different porosities ϕ and an underneath volume ratio V^* = 0.018*

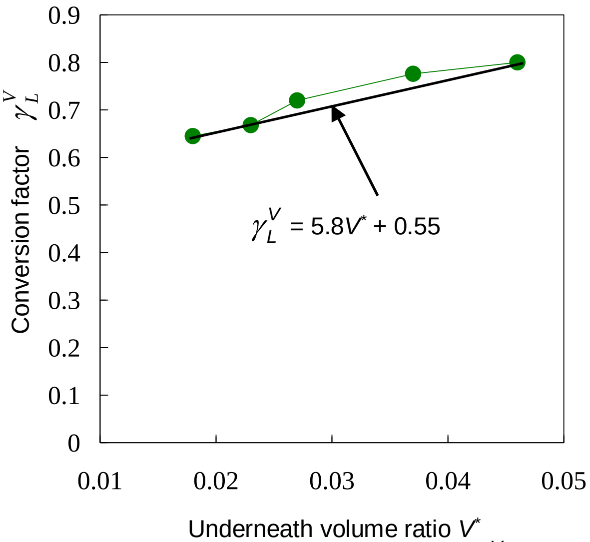


Fig. 8. *Variation of local reduction factor γ_L^{V} with probability of exceeding 2% for different underneath volume ratios V^* and a porosity ϕ = 5%*

Tables 3, 4 and 5 show comparisons of minimum peak local wind force coefficients for porous sunshade roof cover sheets obtained from wind tunnel test, from [4] (using conversion factor γ) and from wind tunnel test for normal building roof (using conversion factor γ). It is clear from this table that all absolute values of minimum peak local wind force coefficient from [4] (using conversion factor γ) $\check{C}_n^{AIJ}$ and from wind tunnel test for normal building roof (using conversion factor γ) $\check{C}_n^{WT}$ for all zones were higher than absolute values of $\check{C}_n$ from wind tunnel test. It means that Eq. 8 can be applied to determine wind loading on porous sunshade roof cover sheet.

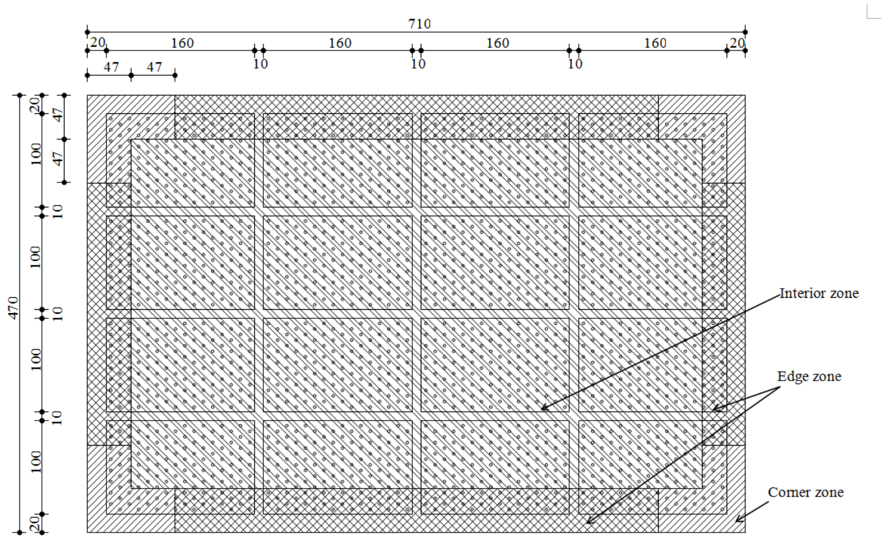


Fig. 9. *Plan of calculation zone of roof (all dimensions in mm)*

Table 3. *Comparisons of minimum peak local wind force coefficients for porous sunshade roof cover sheets for normal building roof for corner zone*

Porosity ϕ	0%	5%	10%	5%	5%	5%	5%
Underneath volume ratios V^*	0.018	0.018	0.018	0.023	0.027	0.037	0.046
Conversion factor $\gamma = -2\phi + 6.4V^* + 0.62$	0.74	0.64	0.54	0.67	0.69	0.76	0.81
Minimum peak wind pressure coefficient on the normal building roof $\check{C}_p^{AIJ}$ (from [4])	–5.4						
Minimum peak wind pressure coefficient on the normal building roof $\check{C}_p^{WT}$ (from wind tunnel test)	–5.9						
Minimum peak local wind force coefficient (from [4] and γ) $\check{C}_n^{AIJ} = \gamma \check{C}_p^{AIJ}$	–4	–3.4	–2.9	–3.6	–3.7	–4.1	–4.4
Minimum peak local wind force coefficient (from wind tunnel test and γ) $\check{C}_n^{WT} = \gamma \check{C}_p^{WT}$	–4.3	–3.7	–3.2	–3.9	–4.1	–4.5	–4.8
Minimum peak local wind force coefficient from wind tunnel test $\check{C}_n$	–2.4	–2.4	–1.9	–2.5	–2.7	–2.9	–3.7

Table 4. *Comparisons of minimum peak local wind force coefficients for porous sunshade roof cover sheets for normal building roof for edge zone*

Zone	Edge zone						
Porosity ϕ	0%	5%	10%	5%	5%	5%	5%
Underneath volume ratios V^*	0.018	0.018	0.018	0.023	0.027	0.037	0.046
Conversion factor $\gamma=-2\phi+6.4V^*+0.62$	0.74	0.64	0.54	0.67	0.69	0.76	0.81
Minimum peak wind pressure coefficient on	–3.2						

the normal building roof $\check{C}_p^{AIJ}$ (from [4])							
Minimum peak wind pressure coefficient on the normal building roof $\check{C}_p^{WT}$ (from wind tunnel test)	–4.9						
Minimum peak local wind force coefficient (from [4] and γ) $\check{C}_n^{AIJ}=\gamma\check{C}_p^{AIJ}$	–2.4	–2	–1.7	–2.1	–2.2	–2.4	–2.6
Minimum peak local wind force coefficient (from wind tunnel test and γ) $\check{C}_n^{WT}=\gamma\check{C}_p^{WT}$	–3.6	–3.1	–2.6	–3.3	–3.4	–3.7	–4
Minimum peak local wind force coefficient from wind tunnel test $\check{C}_n$	–2.4	–2	–1.7	–2.1	–2.2	–2.3	–2.5

Table 5. *Comparisons of minimum peak local wind force coefficients for porous sunshade roof cover sheets for normal building roof for interior zone*

Porosity ϕ	0%	5%	10%	5%	5%	5%	5%
Underneath volume ratios V^*	0.018	0.018	0.018	0.023	0.027	0.037	0.046
Conversion factor $\gamma=-2\phi+6.4V^*+0.62$	0.74	0.64	0.54	0.67	0.69	0.76	0.81
Minimum peak wind pressure coefficient on the normal building roof $\check{C}_p^{AIJ}$ (from [4])	–2.5						
Minimum peak wind pressure coefficient on the normal building roof $\check{C}_p^{WT}$ (from wind tunnel test)	–4.7						
Minimum peak local wind force coefficient (from [4] and γ) $\check{C}_n^{AIJ}=\gamma\check{C}_p^{AIJ}$	–1.8	–1.6	–1.3	–1.7	–1.7	–1.9	–2
Minimum peak local wind force coefficient (from wind tunnel test and γ) $\check{C}_n^{WT}=\gamma\check{C}_p^{WT}$	–3.5	–3	–2.5	–3.1	–3.3	–3.6	–3.8
Minimum peak local wind force coefficient from wind tunnel test $\check{C}_n$	–1.8	–1.5	–1.2	–1.6	–1.7	–1.8	–1.9

4. Conclusion

Conversion factor γ that depends on porosity ϕ and underneath volume ratio V^* of the sheet was recommended in Eq. 8. Based on this factor and minimum peak external wind pressure coefficient from [4] for normal building roof, it is easy to determine wind loading on porous sunshade roof cover sheet through Eq. 8. Finally, this conversion factor will be valuable for calculation of wind loading on porous sunshade roof cover sheets.

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