Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

One consideration on the wind pressure load acting on the surface of mesh membrane structure

- Comparison of experiment and analysis on a simple shape -

Fumiyoshi TAKEDA*, Tatsuya YOSHINO[a] and Yasushi UEMATSU[b]

*Technical Research Center, R&D Division, Taiyo Kogyo Corporation
3-20, Syodai-Tajika, Hirakatashi, Osaka 573-1132, Japan
tf001163@mb.taiyokogyo.co.jp

[a] Technical Research Center, R&D Division, Taiyo Kogyo Corporation, Dr. Eng.
[b] Professor, Department of Architecture and Building Science, Tohoku University

Abstract

In this paper, we have obtained wind force coefficients acting on a membrane roof by the wind tunnel experiment technique and a numerical analysis technique for free-standing canopy with mesh membrane, and will show one consideration on an approach of the numerical analysis to get wind pressure distributions by comparing values of the wind force coefficients that obtained with these techniques. The roof type treated in the paper is a mono-sloped roof. The mesh membrane is porous on the surface, so air of the wind can go through it. This phenomenon affects the wind force coefficients, and this point is a characteristic of mesh membrane. Therefore, it is necessary to reflect this phenomenon on the surface of a model using in the wind tunnel experiment. For the reason, a coefficient on wind pressure loss of the mesh membrane to be called the loss coefficient was actually measured by an experiment, and was reflected the roof model. Furthermore, this loss coefficient was used at the analysis. The measurement experiment to obtain this pressure loss coefficient will be introduced also.

Keywords: Mesh membrane; Wind tunnel experiment; Fluid analysis; Wind force coefficient; Free-standing canopy roof; Mono-sloped roof; Pressure loss coefficient

1. Introduction

Many mesh membrane structures have been built for the purpose of obstructing ultraviolet rays in country such as Australia and the Middle East (see photo 1). In late years, use of mesh membrane as a cover of golf course and for obstructing birds increases in Japan also. Though it is such a circumstance, it seems to be suspicious whether the wind load adequately has been evaluated in design (i.e. structural analysis) for mesh membrane structures. Because there are few data on the wind load for the structures, and there are slightly measurement examples of the study by Letchford[1)] etc. Therefore, the authors are accumulating data of wind force coefficients for mesh membrane roofs of simple shape such as gable, troughed, and mono-sloped roofs by the wind tunnel experiment in the beginning (ref. 3,4). The author thinks that the accumulation of these data will be very important for the design of mesh membrane structures. Furthermore, the author thinks that it will become important in the future to get not only the wind force coefficients but also data of distribution coefficients of local wind pressure with a possibility to cause partial collapse. However, it is no exaggeration to say that there is no data of this wind pressure coefficient. When we want to get this wind pressure coefficients, we can get it by the wind pressure experiment if the membrane is solid material without porousness. The importance of this experiment is firm. However, in the case of mesh membrane, as for the technique of the wind pressure experiment, difficulty is expected by a problem in the model production, and establishment of the experiment technique seems to be a future assignment. Therefore, we examined possibility of an analytical technique that was another approach in this paper. We compared the wind force coefficients of the analysis with the experiment for the mono-sloped roof in the beginning and have given one consideration.

Photo 1: Mesh membrane structures

2. Pressure loss coefficient

2.1. Definition of the pressure loss coefficient

It is difficult to use a real mesh membrane for the roof model in the wind force experiment. Therefore, it is necessary to use a material modelled the mesh membrane for the roof material. We can achieve a similarity of wind loads by using an equal material of the pressure loss coefficient K expressed in an expression (2.1).

$$K = \frac{P_1 - P_2}{\frac{1}{2}\rho V^2} \qquad (2.1)$$

In here P_1 : Windward static pressure (N/mm^2)
P_2 : Leeward static pressure (N/mm^2)
ρ : Air density (Ns^2/m^4)
V : Experiment wind velocity (m/s)

2.2. Pressure loss coefficient measurement experiment

Figure 2.1 shows the device summary used for the measurement. This device consists of two galvanized pipes which have a diameter of 150mm and length of 1,500mm. The pipe is joined with bolts at the center, and it can be divided. A mesh membrane is put at the center of the pipe. And the wind is sent from one end of the pipe with a blower. In the state, the pressure P1, P2 at windward and leeward of the mesh membrane are measured. When the values are substituted for the expression (2.1), the pressure loss coefficient K can be provided.

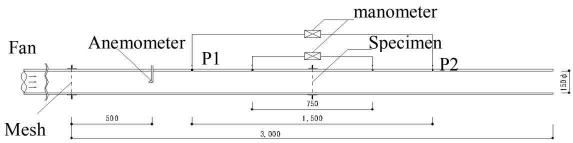


Figure 2.1 Device summary

2.3. Specimen

2.1.1. Mesh membrane

There are various fabrics on mesh membrane from a point of differences such as a cross-section of fibers, how to weave, and the color. In this study, a mesh membrane material which was really used as a roof material in past days was selected among it (see photo 2). This mesh membrane is woven with chemical fibers of the polyethylene coarsely, and the surface is not coated. Therefore, the air and water can go through it. The pressure loss coefficient of this mesh membrane was obtained by the experiment.

2.1.2. Model material

To model material used in the wind tunnel experiment, a material having the pressure loss coefficient equal to it of the real mesh membrane must be chosen. To look for such material, a porous duralumin plate of the 0.4mm thickness (see photo 3) and a porous acrylic plate of the 1.0mm thickness were investigated. These porous plates have many apertures of circle with a diameter of 1.0mm. In addition, the substantiality rate S of the plates was coordinated by adjusting the distance between these circles. There are three kinds of the substantiality rate which are 60%,

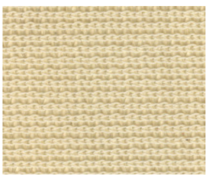


Photo2: Mesh

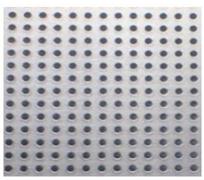


Photo3: Duralumin

Table 2.1 Model materials

Materials	Substantiality rate	Circle diameter	Circle distance
Duralumin Acrylic	80%	1.0mm	2.0mm
Duralumin	70%	1.0mm	1.6mm
Duralumin	60%	1.0mm	1.4mm

70%, and 80% . But regarding the porous acrylic plate, only the plate with substantiality rate of 80% was investigated. Table 2.1 shows the kinds and summary of the porous plates. As mentioned above, the pressure loss coefficient of each porous plate was obtained by the experiment, and the porous plate adopted for the model was decided.

2.4. Measurement method

The measurement was performed by reading the differential pressures at the position of windward and leeward of the specimen with a manometer. It was measured at the wind velocity 5, 10, and 15m/s to grasp Reynolds number influence. Furthermore, regarding only the duralumin plate of S=80%, the measurement ticked away 1m/s between 5-15m/s on the wind velocity.

2.5. Experiment result

Figure 2.2 shows the experiment result. The porous acrylic plate with substantiality rate of 80% showed properties that almost simulated the pressure loss coefficient of the mesh membrane in all wind velocity cases. The coefficient of the porous duralumin plate of substantiality rate of 80% is different from the properties of the acrylic plate at the wind velocity 10m/s greatly. This difference is not solved yet, and it is a future subject. Therefore, the measurement of only the duralumin plate with S=80% ticked away 1m/s at the wind velocity. However, only for the casees of around the wind velocity 5,15m/s, this porous duralumin plate also showed a good approximation. Therefore, the porous duralumin plate with the substantiality rate of 80% was adopted as the model material in this study. This depends on reasons such as a point that the wind tunnel experiment was performed in the wind velocity of V=6m/s.

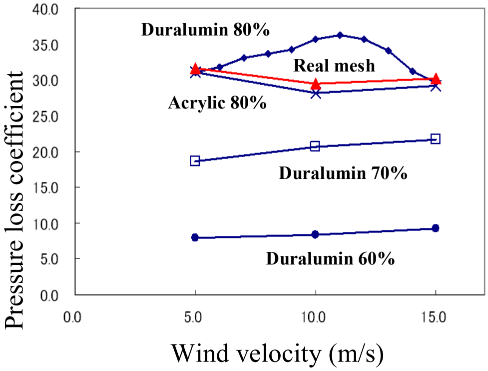


Figure 2.2 pressure loss coefficient

3. Definition of wind force coefficient

3.1. Roof shape

Roof shape is a mono-sloped type, and the size is 15m x 15m in full-scale. The roof has five kinds of incline which are degrees 0, 5, 10, 15, and 20. In addition, substantiality rates of the roof surface are 100% (called **Solid** hereafter) and 80% (called **Porous** hereafter).

3.2. Various wind force coefficients

The expressions (3.1-4) and figures 3.1-2 show definitions of each wind force coefficient to use in the mono-sloped roof. C_{NW} and C_{NL} are coefficients that made the wind force N_W, N_L along the normal direction to the surface, which were acting on the 1/2 surface of the roof, no dimension. In addition, the relations of the expression (3.3) are concluded between C_{NW},C_{NL} and C_L, C_{My}.

$$C_L = \frac{L}{q_H(bl)} \qquad C_{M_x} = \frac{M_x}{q_H(bl^2)} \qquad C_{M_y} = \frac{M_y}{q_H(b^{*2}l)} \tag{3.1}$$

$$C_{N_W} = \frac{N_W}{q_H(b^*l/2)} \qquad C_{N_L} = \frac{N_L}{q_H(b^*l/2)} \tag{3.2}$$

$$\left.\begin{aligned} C_{N_W} &= -C_L - 4C_{My} \\ C_{N_L} &= -C_L + 4C_{My} \end{aligned}\right\} \tag{3.3}$$

$$\left.\begin{aligned} N &= -(N_1 + N_2 + N_3) \\ L &= N \cos \beta \\ M_x &= (N_2 - N_3) \times x_2 \\ M_y &= (N_1 - N_2 + N_3) \times x_1 \end{aligned}\right\} \tag{3.4}$$

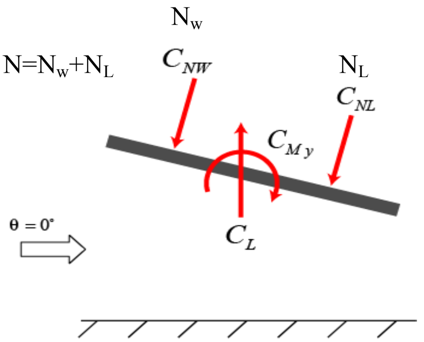


Figure 3.1 Definition-1 of the wind force coefficient

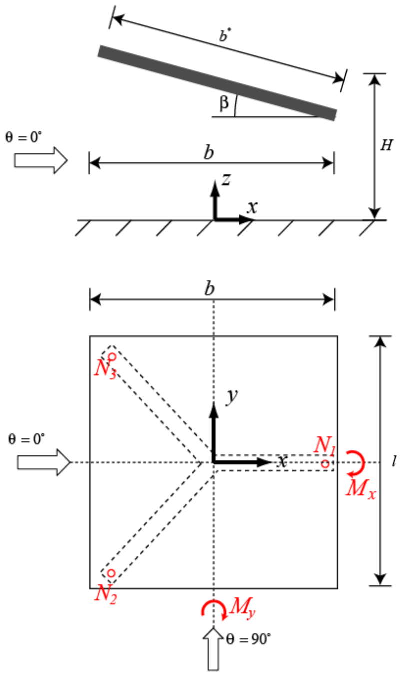


Figure 3.2 Definition-2 of the wind force coefficient

4. Wind tunnel experiment

4.1. Experiment summary

A wind tunnel used for the experiment is the Eiffel type boundary layer wind tunnel, the section of the measurement part is 1.4m in width, 1.0m in height, and 6.5m in length. And the diameter of the turntable is 1.2m. The high-drag strakes and the roughness blocks are arranged on the floor of the wind tunnel properly, and natural wind is simulated. The mean velocity profile for the experiment is a turbulent boundary layer with a power law exponent of $\alpha \fallingdotseq 0.18$.

Wind directions of the experiment are θ =0-180 degrees and the measurement were carryed out with 15 degrees pace. The design wind velocity was supposed to be 31.5m/s. Then, the wind velocity of the model roof at the average height (Z=60mm) becomes UH ≒ 6m/s. In addition, the reduced scale of the wind velocity becomes λ_v=1/5, and the reduced scale rate of time also becomes λ_T=1/5. Six sets of ensemble average were used for the evaluation of various statistics. The scale of the experiment model is 1/100, and it is 15cm x 15cm.

4.2. Anemometry device

Altman[2)] used the anemometry device of a unique Y character model to measure the wind velocity which acted on the whole roof. In this study, an anemometry device was produced in reference to it (see photo 4). The Y character type part of the device, which was made by a spring plate of the thickness 1.2mm of the phosphorus bronze, is put on the top of the column made by aluminum. Post-metal fittings made by aluminum are installed at the end of the spring plate, and the model is installed on the top of the fittings. The external force to act on the model is transmitted to the fittings as axial force N. On the other hand, bending moment to act in the spring plate is provided by strain gauges which were put on the fixed end of the spring plate. Axial force N1,N2,N3, which acts on the spring plate end, is provided by dividing the moment value by the length of the arm of the spring plate (see figure 3.2). In addition, for a purpose to inspect the validity of this experiment, the measurement result of the duralumin plate of the Solid type was compared with the result of the past study of Uematsu[5)], and proper results were provided.

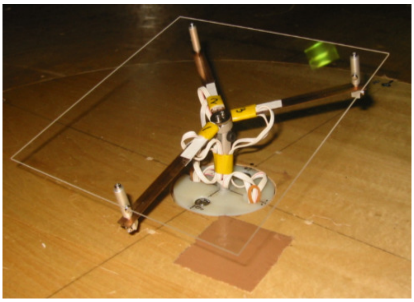


Photo 4: Anemometry device

4.3. Experiment result

Figure 4.1 shows mean values, maximum and smallest peak values of C_L, C_{Mx} and C_{My} in case of the wind direction θ = 0 degrees. C_L values increase with increase of roof inclination angle β. The reduction effect by using Porous is strongly seen at β > 10 degrees. C_{My} values show similar tendency as well as C_L, and the positive peak values decrease by using Porous.

5. Fluid analysis

5.1. Analysis summary

STREAM for Windows (Version7) of commercial software was used for analysis, and it was analyzed with two-dimensional and three-dimensional model. Figure 5.1 shows grid model for the three-dimensional analysis, and the model is half size in the y-direction considering the symmetry. Figure 5.2 shows the size of the analytical area. This area simulated the dimensions of the wind tunnel. The grid division for the area existing the roof

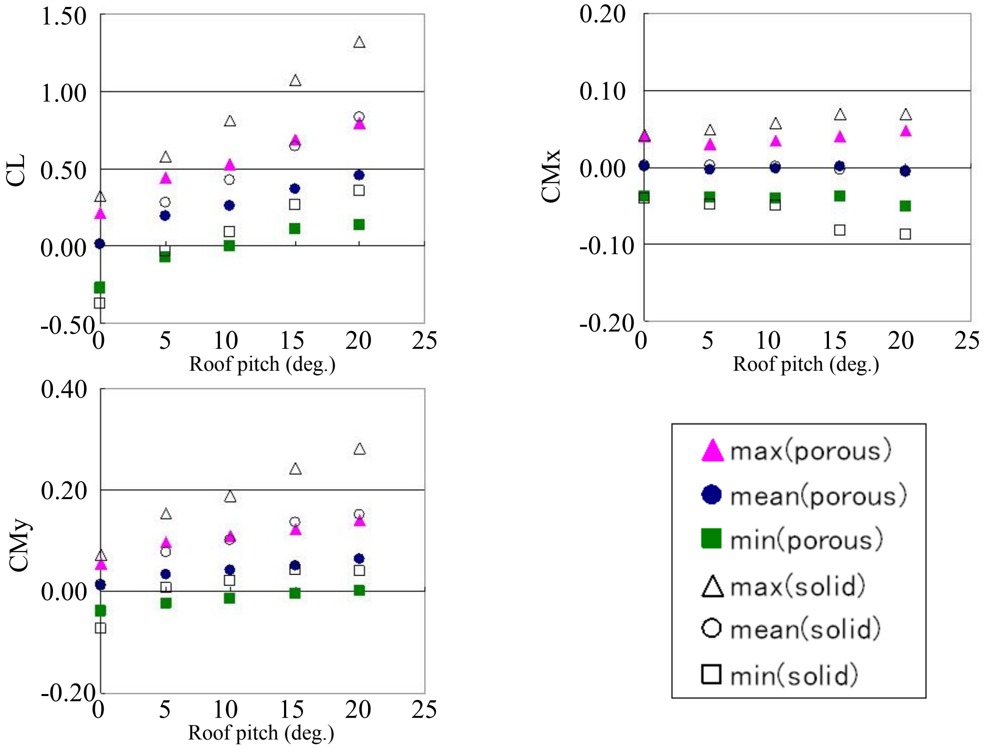


Figure 4.1 Mean, maximum and smallest peak values of C_L, C_{Mx}, and C_{My} (θ =0°)

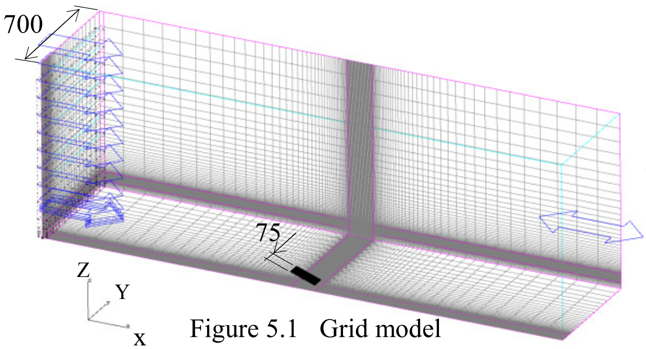


Figure 5.1 Grid model

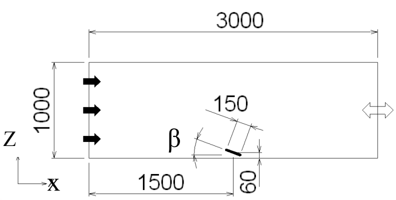


Figure 5.2 Area size

model is divided thickly in comparison with the other area. Figure 5.3 shows the roof model like a stairs, and figure 5.4 shows the zoom up of it. "Component plane", which is an optional component in STREAM, was appointed on the surface of each grid with the roof plane in case of Solid model, and "Condition area" was appointed in case of Porous model. The wind direction is only θ = 0 degrees for the analysis.

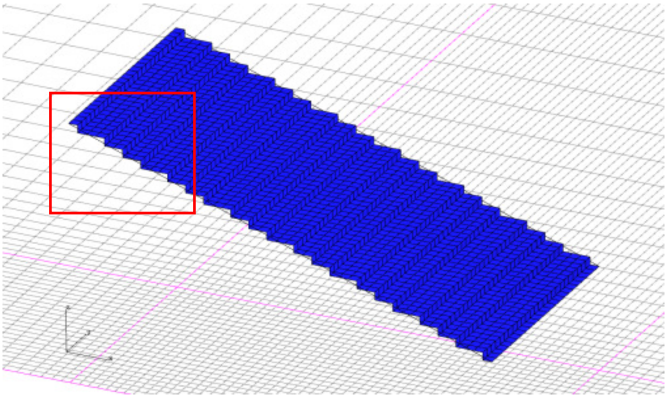


Figure 5.3 Roof plane model

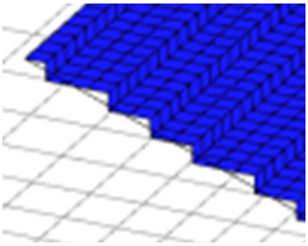


Figure 5.4 Zoom up

Table5.1 Boundary condition

Surface at Xmin	< Power law boundary > $$U_Z = U_G \left(\frac{z}{z_G} \right)^{\alpha}$$ Speed at criteria elevation : U_G = 8 m/s criteria elevation : Z_G = 0.6 m Land surface elevation : 0 m The number of the powers : α = 1/6 < Turbulent flow > Turbulence intensity : Using experiment values (See Table5.2)
Surface at Xmax	Surface pressure boundary Pressure : 0 Pa
Surface at Ymin, Ymax, Zmax	Free-slip wall
Surface at Zmin	No-slip wall (Power law) The number of the powers : 1/6
Component surface	No-slip wall (Logarithmic law) Only panel of Solid is effective

Table 5.2 Turbulence intensity

Z (m)	Values
0 ～ 0.01	0.186
～ 0.02	0.179
～ 0.03	0.186
～ 0.05	0.172
～ 0.1	0.158
～ 0.2	0.111
～ 0.3	0.087
～ 0.4	0.063
～ 0.5	0.047
～ 1.0	0.035

The pressure loss coefficient was appointed with Cf =31.7 then. Calculation method was the finite volume method, and RNG k-ε equation model was used as a turbulence model. The initial condition of the speed is 6m/s in X direction. Table 5.1 shows boundary condition. As for the calculation, it was performed nine cases of inclination angles β =-20,-15,-10,-5,0,5,10,15,20 degrees in each model.

5.2. Analysis result

Figure 5.6 shows cutting planes for displays of vector and distribution in figures 5.8-10. Figure 5.7-8 show the wind velocity vectors of Solid and Porous in case of inclination degrees β =20. Figure 5.7 shows the vector state on the vertical section at the center of the wide length along the Y direction. Figure 5.8 shows the vector state in the parallel section at the upward position of the roof surface. From the comparison of the vector state of Solid and Porous, difference can be found in the occurrence state of vortex. In case of Porous, the occurrence of vortex is not seen whereas the vortex of circulation flow is seen at the leeward in case of Solid. It seems that stream of air, which penetrated the surface of the mesh membrane, controlled the occurrence of vortex. In addition, the analysis of Porous had better convergence characteristic on the calculation than the analysis of Solid. Furthermore, figure 5.9-10 show the wind pressure distribution state at the same time. Figure 5.9 shows the distribution state on the top surface of the roof. Figure 5.10 shows the state on the bottom surface. The distribution of pressure changes among -27 to 23 Pascal in case of Solid, and changes among -6 to 12 Pascal in case of Porous. The pressure values of Porous decrease in comparison with the values of Solid greatly. In addition, in case of Solid, as for the pressure values of the windward, about four or five times become big in comparison with the leeward values on the top surface of the roof. On the other hand, the pressure values make a little difference in case of Porous. On the bottom surface, as for the pressure values of the windward, about around 3-5 times become big in comparison with the leeward values in case of both of Solid and Porous, and it is shown that both pressure distribution states are similar. In case of Porous, the reason why the pressure distribution state makes a little difference in the top surface is as follows. It seems that it prevents a rise of the wind pressure value that air goes through in the top surface from the bottom. The case of other inclination angles showed a similar tendency as things mentioned above.

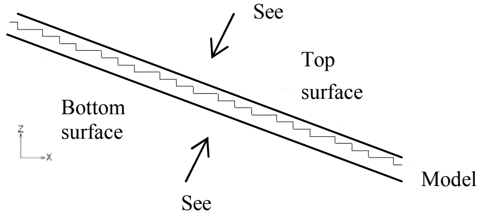
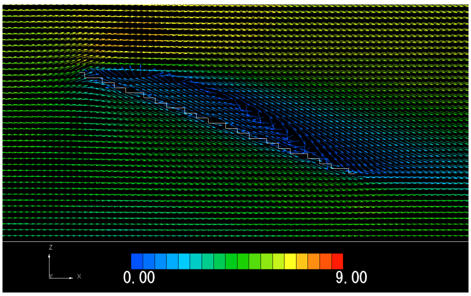
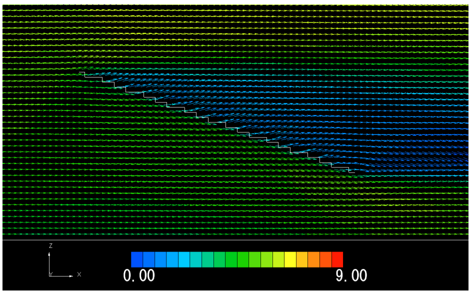


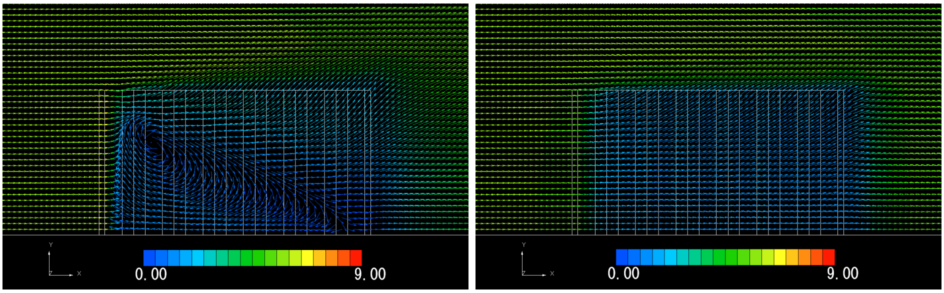
Figure 5.6 Cut planes





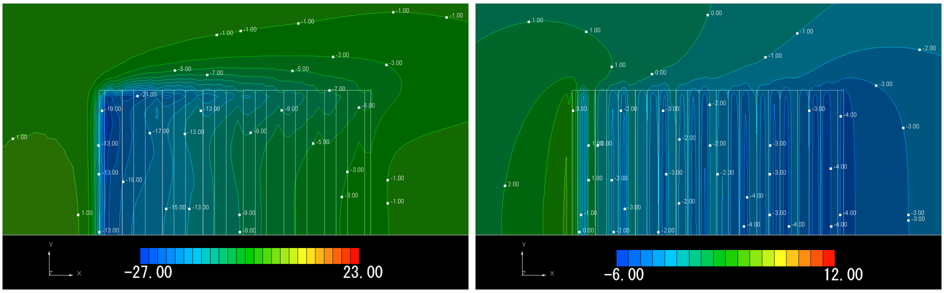
Solid 20° 3D　　　Porous 20° 3D

Figure 5.7 Distribution of the average wind velocity vector (Vertical section)



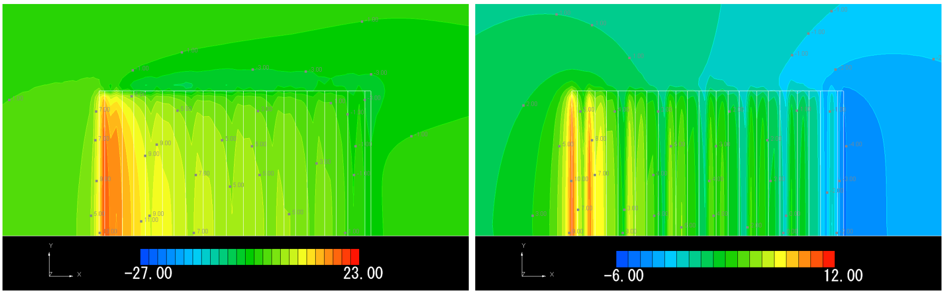
Solid 20° 3D Porous 20° 3D

Figure 5.8 Distribution of the average wind velocity vector (Top surface)



Solid 20° 3D Porous 20° 3D

Figure 5.9 The wind pressure distribution （Top surface）



Solid 20° 3D Porous 20° 3D

Figure 5.10 The wind pressure distribution （Bottom surface）

6. Comparison

Figure 6.1-2 shows comparison of the C_L and C_{My} of the wind coefficient provided from the experiment and the analysis. The horizontal axis in the figure shows the angle of inclination β of the roof, and the vertical axis shows the C_L values of the wind force coefficient. Figure 6.1 shows that the absolute values of C_L by 2-dimensional(hereafter 2-D) analysis have higher about 1.64 times in a mean than the experiment values in case of Solid, and a difference is big at +10,-10 degrees in particular. On the other hand, it shows that the behavior of C_L values by 3-dimensional (hereafter 3-D) analysis is near to the behavior of the experiment. In case of Porous, it shows that the behavior of C_L by both of 2-D, 3-D analysis is near to the experiment values. Next, figure 6.2 shows that C_{My} values by 2-D analysis is higher about 1.39 times in a mean than the experiment values. However, polygonal lines of Solid drop when it exceeds +10,-10 degrees. On the contrary, in case of Porous, the absolute values of the experiment values are higher than the analytical value, and the analytical values are about 0.51 times of the experiment values. However, behavior of both is similar in the negative side. It is an assignment of hereafter to investigate the difference of the positive side.

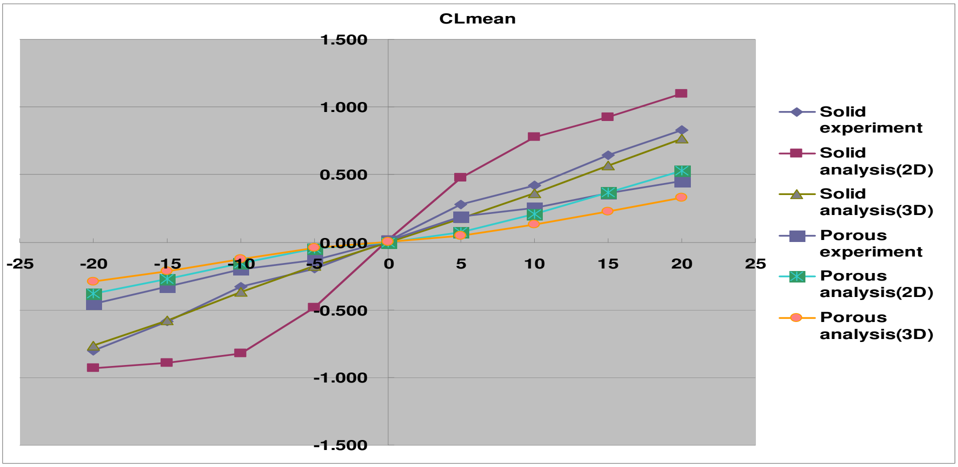


Figure 6.1 Comparison of the wind force coefficient C_L

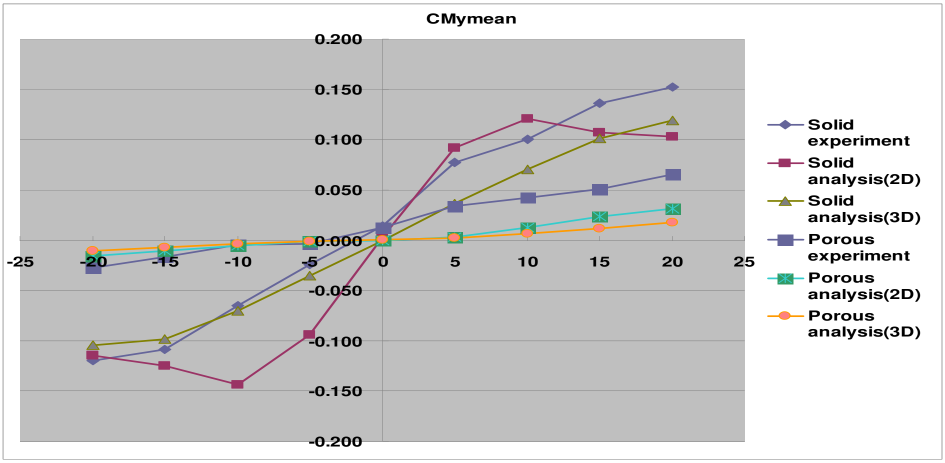


Figure 6.2 Comparison of the wind force coefficient C_{My}

7. Conclusion

Conclusions are shown as follows.

1) The acrylic plate with substantiality rate of 80% was the nearest to the real mesh membrane on the pressure loss coefficient.
2) However, the duralumin plate with substantiality rate of 80% also showed a good approximation only for around the wind velocity 5,15m/s.
3) Therefore, the duralumin plate with substantiality rate of 80% was used as the model material for the wind tunnel experiment.
4) The wind pressure distribution state on the bottom surface of Porous roof was not very different from Solid, but was different greatly on the top surface. It seems that it depends on influence of the air which goes through the mesh membrane.
5) In case of Solid membrane, the C_L values provided by 3-D analysis showed good approximation to the experimental values.
6) The convergence characteristic on the calculation of the analysis for the Porous membrane was good, because the occurrence of vortex of the Porous roof was prevented by the air, which went through the mesh membrane, than the Solid.
7) Therefore, the Porous membrane seemed to be suitable for the numerical analysis technique than the Solid membrane.
8) Thus, it seems that it will be worth to investigate the analytical approach for getting the wind pressure distribution to the other roof shape in future.

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