The Wind Response on Horn-shaped Membrane Roof and Proposal of Gust Effect Factor for Membrane Structures

Wind loading is the most dominant load for membrane structures. Especially, the conic shaped membrane roof, namely the horn-shaped membrane roof, has characteristic curved surface shape. Therefore, it is expected that the aerodynamic characteristics around this roof are very complicated. On the other hand, since the membrane is low stiffness material, the response of membrane structure depends on the pre-stress. Therefore, a setting value of pre-stress is the most important factor of the membrane design for the wind load with turbulence.

From these backgrounds, this research focuses on the one-unit horn-shaped membrane roof and indicates representative wind pressure on it, using wind tunnel test which was under the turbulent flow. Additionally, we evaluated the responses of membrane roof for the wind load by the response analyses. Finally we suggest the gust effect factor for membrane structure, namely "G_{fm}", as the new evaluation technique of the wind load for the membrane structure, and indicate some examples of G_{fm} value.

1. Definition of "gust effect factor for membrane structure (G_{fm})

1.1 Original gust effect factor GEF

The "gust effect factor" (GEF) was originally suggested by A.G. Davenport in1961. The GEF is a dimensionless coefficient that quantifies the effect of turbulence on wind pressure distribution and enables the assessment of maximum external loading and internal forces in the structure from the analysis of the mean wind pressure scenario. The GEF is employed by code of many countries.

Generally, the GEF is calculated by the ratio between the maximum load effect and the mean load effect shown in following equation, figure 1 and figure 2.

$$GEF = \frac{\text{maximum load effect}}{\text{mean load effect}} \quad (1)$$

The Building Standard Law of Japan provides the GEF from 1.8 to 3.0 depending on the roughness of terrain and the dimension of buildings.

1.2 "Suggestion of gust effect factor for membrane structure (G_{fm})"

The original GEF value was given on the assumption that the building consist of rigid structures. However, the membrane structure has a characteristic of low stiffness and resists only tensile force. Additionally, the membrane structure needs the initial tensile force to resist the external load as the wind load. For all these reasons, the value of average membrane stress obtained from dynamic response analysis disagrees with membrane stress obtained from static analysis. Therefore, this paper suggests new type of the gust effect factor for the membrane structure which is calculated based on the concept of the GEF, namely "Gust effect factor for membrane structure (G_{fm})". The G_{fm} is obtained from follows;

$$G_{fm} = \frac{\sigma_{dynamic\_max\_i}}{\sigma_{static\_max}} \quad (2)$$

in which '$\sigma_{dynamic\_max\_i}$' is the value of the maximum membrane stress on the element number 'i' during 600sec from dynamic response analysis using the time history wind load, and 'σ_{static_max}' is the value of the maximum effective stress for the average wind pressure during 600sec (Fig. 3). Since G_{fm} value takes account of the membrane pre-stress, this value can be used as the design wind load without the dynamic response analysis to design the membrane structures.

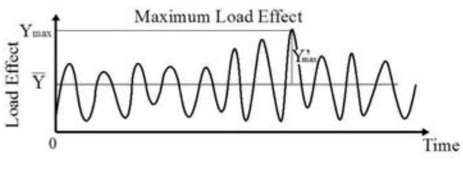

Figure 1. Time variation of load effect by dynamic action of wind

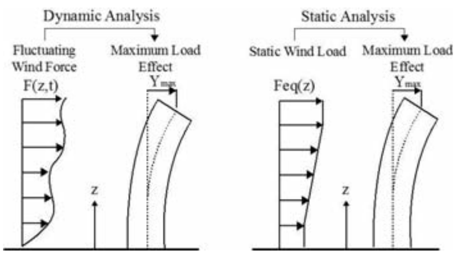

Figure 2. The concept of effective static wind load

2. Wind tunnel test

2.1 Outline of test

This test measured wind pressure coefficients on the stand-alone model of horn-shaped membrane roof using the Eiffel type wind tunnel as shown in figure 4. The turbulent boundary layer flow was made by the roughness blocks, the spires and the trips. Table 1 shows conditions in this test. It was assumed that a model scale was 1/ 100 and that a velocity scale was 7/27 at the full scale wind speed 34m/s. In this case, time scale was 11/125.

The 100mm x 100mm square based model was used in this test. Major parameters were three types of rise-span ratio, namely h/L=0.1, 0.2 and 0.3, and the presence of walls. Six types of model were prepared for this wind tunnel test. The outline of models and measurement taps show in figure 5.

These models were made from acrylic plastic. As for the open type model, the roof depth was about 5mm in order to measure both sides of the roof at the same time (Fig. 6). Additionally, wind directions were only four types which were 0-deg., 15-deg., 30-deg. and 45-deg., because of symmetry form of roof. Airflow conditions which were the average wind speed profile, the turbulence intensity, the power spectral density of fluctuating wind speed and the scale of

Table 1: Conditions of wind tunnel test

Wind tunnel facility	Eiffel type wind tunnel
Flow	Boundary Turbulent Layer Flow (Urban Area; Terrain 3 in The Building Standard Law of Japan)
Sampling speed	500Hz
Sampling time	30sec
Wind velocity	About 7 m/s at z=35mm
Rise-span ratio h/L	0.1, 0.2, 0.3
Model scale	100mm x100mm (model : full =1:100)
Wall	Open type / Enclosed type
Wind direction	0-degree, 15-degree, 30-degree, 45-degree
Number of test on each model	Five times

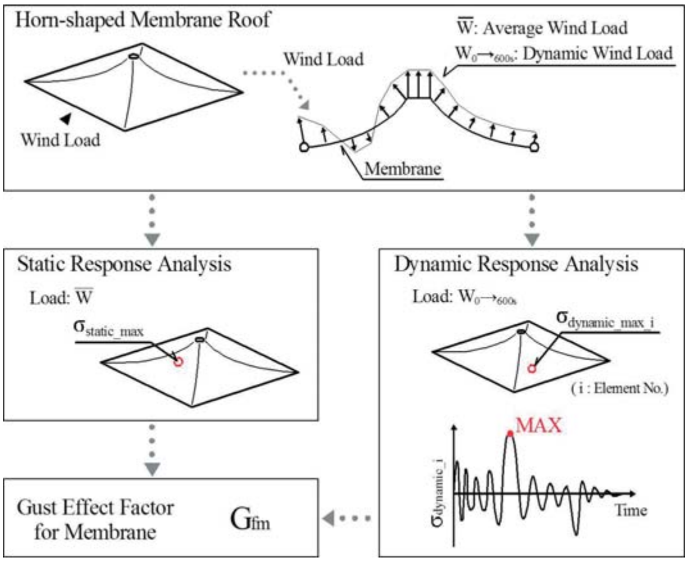

Figure 3. Definition of gust effect factor for membrane G_{fm}

Figure 4. Wind tunnel test

Figure 6. The photo of models; three types of h/l models which was made from acrylic plastic. The depth of open type's roof is about 5mm thick.

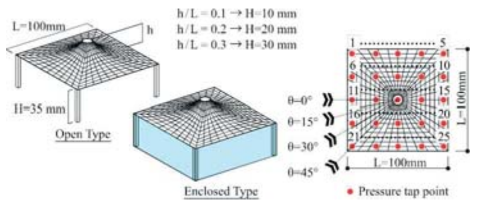

Figure 5. The outline of models; two types model was prepared, namely "open type" and "enclosed type", and there are 25 pressure taps on the roof in each model.

turbulence for this test (Fig. 8). The velocity gradient α was 0.2 and the turbulent intensity around the roof was about 0.3. This wind was simulated natural wind in the urban area, namely "terrain 3" in the Building Standard Low of Japan.

3. Results Obtained from Wind Tunnel Tests

Distributions of wind pressure coefficient (Cp) and fluctuating wind pressure coefficient (Cp') on each model are indicated in figure 7. The Cp and the Cp' changed the distributions depending on the presence of the wall. Particularly, the Cp' of the enclosed model was larger than that of the open type. These results may cause some effects on the response of membrane, since the membrane structure is generally sensitive structure for the external force such as wind load with turbulence.

4. Response analyses under wind load

4.1 Analysis conditions

Static analysis and dynamic analysis were carried out based on following conditions. Simulation models, material conditions and a calculation method of the wind load are shown in figure 8. The shape of the basic model is horn-shaped membrane roof covered over the plan of 10m x 10m. Additionally, this model has a ring and a strut to keep stable of membrane surface in the middle of roof. And the spring at the lower end of the strut resist only compressive force. Rise-span ratios of the roof are 0.1, 0.2 and 0.3, and initial tensile forces of the membrane, i.e. "pre-stress", are 1kN/m, 2kN/m and 4kN/m. A damping on the dynamic analysis was given by the Rayleigh damping model and a damping constant of this membrane was assumed 3% in this paper. The external forces are the wind loads obtained from the wind tunnel test on Section 3. Average wind pressures were used in the static analysis and time history wind pressures were used in the dynamic analysis.

4.2 Results of response analyses

Effective stresses which were obtained from static analyses at the wind velocity pressure of 455N/m^2 are shown in figure 9. And results obtained from the dynamic analysis are shown in figure 10. This figure shows the time history effective stress on the middle points of the

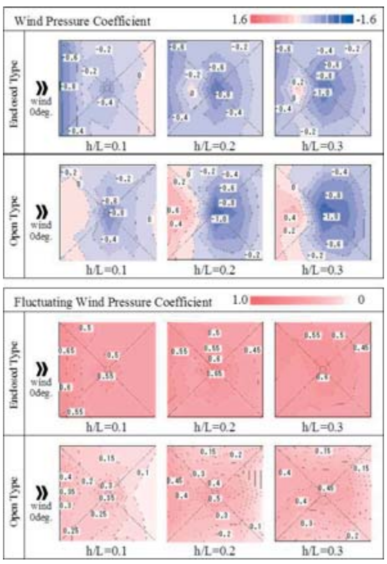

Figure 7. Mean wind pressure coefficient and fluctuating wind pressure coefficient which were obtained from wind tunnel tests

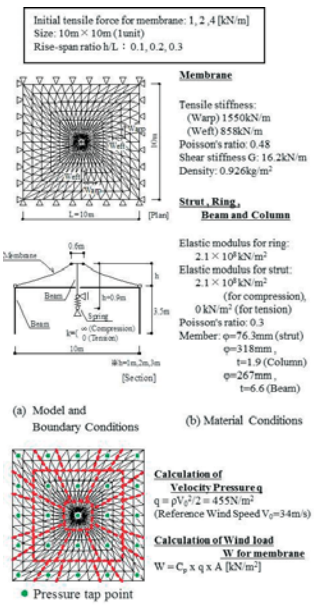

Figure 8. Analysis conditions

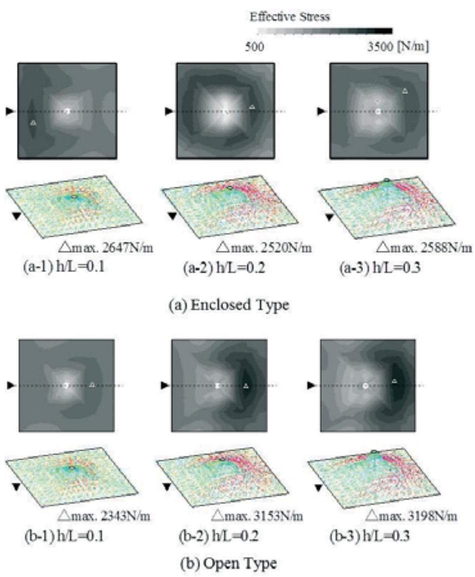

Figure 9. Effective stress and maximum value of it when the wind velocity pressure q is 455n/m^2.

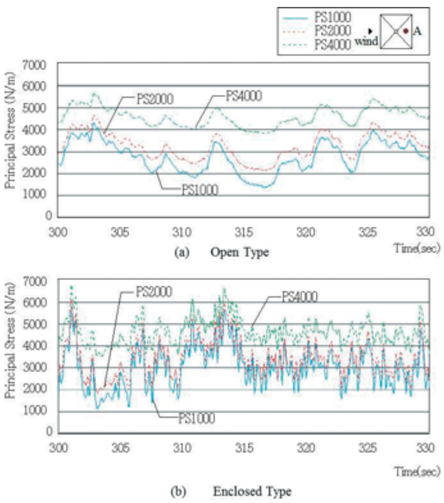

Figure 10. Effective stress - time history at time 300sec and 330sec

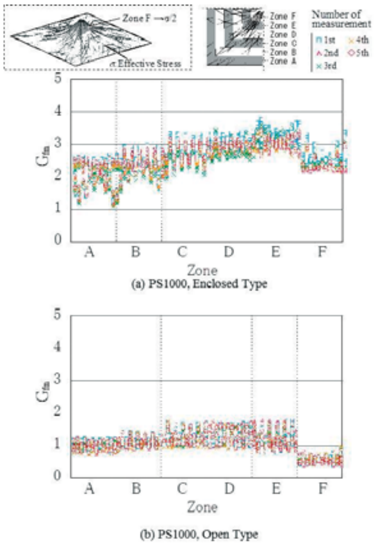

Figure 11. G_{fm} value on each element; h/l=0.2 ps1000, enclosed type and open type

span on the membrane which model is h/L=0.2 under the wind direction 0-degree. The fluctuation of the enclosed type was stronger than the open type as for the membrane stress.

The static analysis result shows that stress distribution changed depending on rise-span ratio. And the value of maximum effective stress of the enclosed type was smaller than that of the open type.

On the other hand, the dynamic response analysis indicated that the dynamic response correlates highly with the " Cp' " value. And maximum stress of the enclosed type is larger than that of open type. This study shows that the result of dynamic response analysis leads to the opposite result of static response.

5. Examples of G_{fm} calculation

The G_{fm} value was calculated for the stand-alone horn-shaped membrane structure according to the equation (2). '$\sigma_{dynamic\_max\_i}$' and 'σ_{static_max}' are the result of the average static response analyses and the dynamic response analyses. Fig ure11 shows the G_{fm} value on each element on the PS1000 and h/L=0.2 model under the wind direction 0-degree. And all of results, i.e. the results of five times per model analysis were model were indicated in the same figure. In calculation of G_{fm}, stress value of zone-F was reduced to half of original value based on the assumption that the membrane of this zone was generally laminated. This figure indicates that the presence of the wall is one of the key factors to evaluate the G_{fm} value, and the value of it increases with distance from the circumference of the model.

In the same way, another parameter was calculated and plotted the maximum value of all elements for each parameter, respectively (Fig. 12). The value of the enclosed type is larger than that of the open type. And the larger the value of pre-stress become, the smaller the value of G_{fm} became. But the wind direction has little or no effect on the G_{fm} value.

Finally, the comparison between the G_{fm} value and the original GEF value which is 2.5 under the same conditions as the wind tunnel test based on the Building Standard Law of Japan are show in figure 13. This figure shows the average value of G_{fm} and liner approximation of G_{fm} on each model and ratio of G_{fm} to GEF. The value of PS1000 and PS2000 on the enclosed type, and PS1000 and PS2000 on the open type, h/L=0.1 and 0.2 exceed G_{fm} /GEF =1.0. This study grasped the fact that the low pre-stress model, which is designed using the present GEF value, doesn't perform the design criteria.

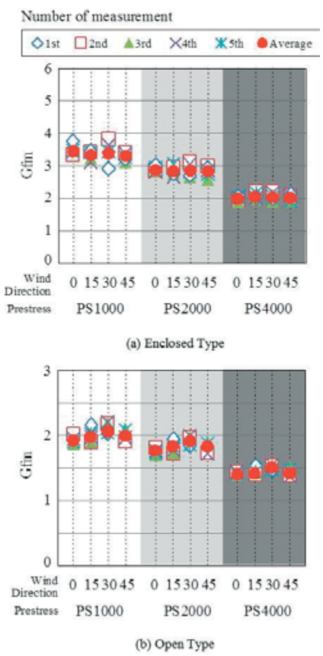

Figure 12. G_{fm} depending on pre-stress and wind direction on each model type

6. Conclusion

The membrane structures are designed on the assumption that pre-stress is provided. On the other hand, the usual GEF value has been used for the calculation of the wind load in many countries. This paper shows the value of the GEF correlate with the value of the initial tensile force of the membrane and suggested the gust effect factor for membrane structure, namely G_{fm}, which is taken into account the initial tensile force of the membrane. This value can be used instead of the original GEF according to form and pre-stress. This paper shows some examples of G_{fm} value for membrane structure. This concept can be used successfully in other type of tension structure.

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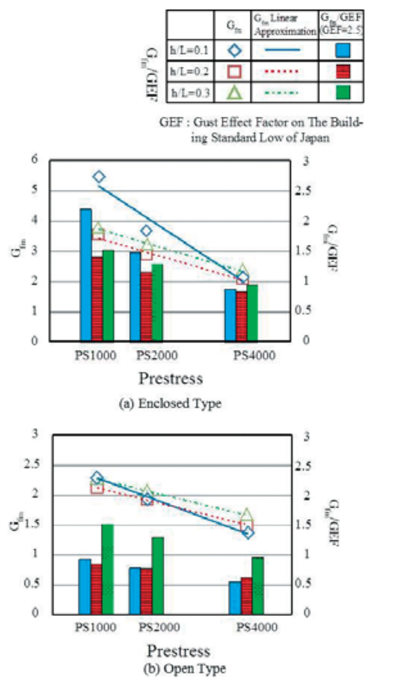

Figure 13. G_{fm} for the design wind load and comparison with gef of the building standard low of japan (gef=2.5)