Wind Loading on a Hyperbolic Paraboloid Free Roof

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Abstract: Wind loading on an H.P. (hyperbolic paraboloid) free roof has been investigated on the basis of a wind tunnel experiment. The roof models of 1 mm thickness were made of nylon resin using laser lithography. The parameters under consideration are the rise to span ratio and slope of the roof. The overall aerodynamic forces and moments were measured by a six-component force balance in a turbulent boundary layer. Based on a combination of the lift and moment coefficients, the design wind force coefficients, C_{NW}^* and C_{NL}^* , on the windward and leeward halves of the roof are proposed. Focus is on the column axial forces induced by wind loading as the load effect for discussing the design wind loads, assuming that the roof is rigid and supported by four corner columns. Indeed, two pairs of C_{NW}^* and C_{NL}^* , generating the maximum tension and compression in the columns, are provided for each of the two or three wind directions parallel to the roof's diagonal lines. The proposed values of the wind force coefficients are compared with the specified values in the Australia/New-Zealand Standard for a limited range of rise to span ratio.

Key words: Free roof, hyperbolic paraboloid, wind force coefficient, wind tunnel experiment, codification.

1. Introduction

H.P. (hyperbolic paraboloid) free roofs are widely used for structures providing shade and weather protection in public spaces, such as sports grounds and shopping areas. Pre-tensioned membrane is often used for such roofs. The roofs are consequently very lightweight structures that are vulnerable to wind actions. In practice, such roofs often experience damage during windstorms. Therefore, the wind resistance is one of the greatest concerns for structural engineers when designing these roofs. However, few specifications of design wind loads on H.P. free roofs are provided in building codes and standards. Although the AS/NZ (Australia/New Zealand) Standard [1] provides the wind force coefficients, the range of roof geometry is rather limited.

Since free roofs are usually supported by columns and no walls exist, wind action is directly exerted both on the top and bottom surfaces. Consequently, the flow around the roof is rather complicated. Whereas, a large

database of knowledge exists for wind pressure distributions on enclosed buildings of various shapes, e.g., Dutt [2-4], only a few studies have been made on the wind loading on free roofs [5], which may be due to difficulties in model making and wind pressure measurement.

Uematsu et al. [6] proposed the design wind force coefficients both for the main wind force resistant systems and for the C & C (cladding and components) of planar free roofs based on a series of wind tunnel experiments. They made simultaneous pressure measurements for gable, troughed and mono-sloped roofs in a turbulent boundary layer. They focused on the axial forces induced in the columns as the load effect for discussing the design wind loads, assuming that the roof was rigid and simply supported by four corner columns.

In addition to such basic shapes that Uematsu et al. [6] tested, H.P. roofs are often used for membrane structures. Beutler [7] measured the mean wind pressures on H.P. free roofs. Regarding the wind-induced response of H.P. free roofs, Pun and Letchford [8] reported the analytical results of an H.P. tension membrane roof subjected to fluctuating wind

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loads. Recently, Kaseya et al. [9] measured the distribution of wind force coefficients on an H.P. free roof in a turbulent boundary layer. Using the time history of wind force coefficients at 25 points on a rigid model obtained from the wind tunnel experiment, Nakagawa et al. [10] investigated the dynamic response of membrane roofs. The thickness of the wind tunnel models was 5 mm, while the length of the side was 100 mm. The models were so thick that the flow around the models seemed to be distorted [11, 12].

To the authors' best knowledge, no study has been made on the design wind loads on H.P. free roofs with a wide range of roof geometry. Simultaneous pressure measurements at many points both on the top and bottom surfaces are quite difficult for H.P. free roofs because of the difficulties in model making and pressure measurement. In the present study, therefore, a force balance technique is employed.

The present paper discusses the wind force coefficients for designing H.P. free roofs on the basis of a wind tunnel experiment with rigid models. The overall aerodynamic forces and moments are measured by a six-component force balance in a turbulent boundary layer. The basic idea for specifying the wind force coefficients is the same as that the authors used for the gable, troughed and mono-sloped roofs [6]. The proposed wind force coefficients are compared with the specifications of the Australia/New Zealand Standard. A comparison is also made from the viewpoint of load effect.

The roof deflects and oscillates under wind loading,

which may affect the wind forces on the roof due to flow-structure interaction. However, as the first step of study, this effect is neglected in the present paper. Takeda et al. [13] have recently made a brief discussion on the effect of mean deformation of H.P. membrane roofs on the mean wind forces using a CFD (computational fluid dynamics) analysis. It should be mentioned that the present paper is a revised and advanced version of the authors' previous papers [14, 15], focusing on the design wind force coefficients.

2. Experimental Arrangement and Procedures

The experiments were carried out in a turbulent boundary layer with a power law exponent of $\alpha = 0.21$ for the mean velocity profile. Three models with different rise to span (or sag to span) ratios were made of nylon resin using laser lithography (Fig. 1). The thickness of the roof models was 1 mm. The notation and coordinate system used in the present paper are shown in Fig. 2. The lift L , positive upward, and the aerodynamic moments M_x and M_y about the x and y axes were measured by a six-component force balance (SSKLBW60-1). They are reduced to coefficients as follows:

$$C_L = \frac{L}{q_H S} \quad (1)$$

$$C_{Mx} = \frac{M_x}{q_H S a'} \quad (2)$$

$$C_{My} = \frac{M_y}{q_H S a'} \quad (3)$$

Fig. 1 Experimental models: (a) shape and dimension (mm); (b) wind tunnel model with $h/a = 1/2$.

Fig. 2 Notation and coordinate system: (a) aerodynamic force and moments; (b) roof slope.

where, q_H = time-averaged velocity pressure of the flow at the mean roof height H (80 mm); S = projected plan area of the roof (a^2) and $a' = (\sqrt{2}/3)a$, which is used as a reference length of the models; $a = 150$ mm. The roof slope β_x obtained by rotating the roof about the x -axis was changed from 0° to 40° . The wind direction θ was changed from 0° to 90° for $\beta_x = 0^\circ$ and from -90° to 90° for $\beta_x > 0^\circ$.

The measurements were carried out at a wind velocity of $U_H \approx 9$ m/s at the mean roof height H . The turbulence intensity I_{uH} at this height was approximately 0.17. The geometric scale λ_L and the velocity scale λ_V were assumed 1/100 and 1/3, respectively, resulting in a time scale of $\lambda_T = 1/33$. The outputs of the force balance were sampled simultaneously at a rate of 200 Hz for a period of 19 s, which corresponded to 10 min in full scale. The measurements were repeated six times under the same condition. The statistics of the aerodynamic coefficients were evaluated by applying ensemble average to the results of these six consecutive runs. The wind forces on the three legs of 5 mm diameter supporting the roof were measured separately and were subtracted from the overall loads to produce load on the roof alone.

The Reynolds number Re , defined in terms of U_H and a , is approximately 9×10^4 . The great concern is the Reynolds number effect on the aerodynamics, because the H.P. free roof consists of curved surface. The Reynolds number effect is related to the change in location of flow separation point on the curved

surface. The results of flow visualization using oil-film method [15] and CFD analysis [16] indicate that the wind flows along the top surface of the roof when $\theta = 0^\circ$, the flow does not separate from the top surface even when $h/a = 1/2$. Regarding the bottom surface, the flow separates at the leading edge of the roof and generates conical vortices on the bottom surface. From these results, the Reynolds number effect seems small for H.P. free roofs under consideration here.

3. Experimental Results

3.1 Wind Forces on Roofs with No Slope

Fig. 3 shows the statistical values of C_L , C_{Mx} and C_{My} as a function of wind direction θ for $h/a = 1/2$. The mean, maximum and minimum peak values of these aerodynamic coefficients are plotted in Fig. 3. The lift coefficient C_L becomes the maximum (upward) when $\theta \approx 0^\circ$ and the minimum (downward) when $\theta \approx 90^\circ$. This feature is related to the increased wind velocity along the convex surface, i.e., the top surface when $\theta \approx 0^\circ$ and bottom surface when $\theta \approx 90^\circ$. The magnitude of the negative peak value of C_{Mx} becomes the maximum when $\theta \approx 90^\circ$, while that of C_{My} becomes the maximum when $\theta \approx 0^\circ$. The absolute values of C_{Mx} for $\theta \approx 0^\circ$ and those of C_{My} for $\theta \approx 90^\circ$ are relatively small. The variation of C_{Mx} with θ is opposite to that of C_{My} . Almost the same features were observed for $h/a = 1/3$ and $1/6$. Furthermore, it was found that the magnitude of the maximum and minimum peak values increases with an increase in h/a .

The axial forces N induced in the columns were computed by using the time history of C_L , C_{Mx} and C_{My} obtained from the wind tunnel experiment, assuming that the roof was rigid and simply supported by four corner columns. In the present study, focus is on the axial forces induced in the columns as the load effect for discussing the design wind loads. The maximum and minimum peak values of the non-dimensional axial forces $N^* = N/(q_H S/4)$ among the four columns are plotted in Fig. 4. Noting that the non-dimensional axial forces induced in the four columns are represented by N_a^* to N_d^* (Fig. 4e). As might be expected from the results in Fig. 3, the peak

values of N^* are large in magnitude when $\theta \approx 0^\circ$ and 90° . However, this is not always the case. The maximum peak values are induced in oblique winds in some cases.

These experimental results imply that the fluctuating wind forces on the roof are mainly caused by the turbulence in the approach flow. The design wind loads can be specified as the equivalent static loads, in which the dynamic load effect is considered in the evaluation of gust effect factor. The basic values of the wind force coefficients can be specified based on the results for $\theta = 0^\circ$ or 90° , which should be modified by considering the effect of wind direction on the load effect.

Fig. 3 Variation of the aerodynamic coefficients with θ ($h/a = 1/2$, $\beta_x = 0^\circ$): (a) C_L ; (b) C_{Mx} ; (c) C_{My} .

Fig. 4 Variation of non-dimensional axial forces N_a^* to N_d^* with θ ($h/a = 1/2$, $\beta_x = 0^\circ$): (a) N_a^* ; (b) N_b^* ; (c) N_c^* ; (d) N_d^* ; (e) notation of axial forces.

Fig. 5 Effect of β_x on the aerodynamic coefficients ($h/a = 1/2$): (a) C_L ; (b) C_{Mx} ; (c) C_{My} .

3.2 Effect of Roof Slope on the Aerodynamic Coefficients

Fig. 5 shows the effect of β_x on the statistical values of C_L , C_{Mx} and C_{My} for $h/a = 1/2$. As mentioned above, the negative peak value of C_L becomes large in magnitude at $\theta \approx 90^\circ$. This peak value increases further with an increase in β_x up to about 20° . This may be due to the increased flow velocity along the bottom surface, generating a large negative lift force. The effect becomes the greatest when $\beta_x \approx 20^\circ$. Such an increase in $|C_L|$ generates an increase in $|C_{Mx}|$. The positive peak values of C_L for $\theta < 0^\circ$ increases with increasing β_x . In particular, the value of C_L is rather large when $\theta \approx -45^\circ$. In such a wind direction case, the value of C_{Mx} is also rather large. On the other hand, the effect of β_x on C_{My} is relatively small. Similar results were observed for $h/a = 1/3$ and $1/6$.

4. Discussion of Design Wind Force Coefficients

4.1 Dynamic Load Effect

In order to investigate the dynamic effect of flow turbulence on the column axial forces, the gust effect factor G_f , defined as the ratio of the maximum or the minimum axial force to the mean value induced in the column, was computed. Fig. 6 shows the results for G_f plotted against the mean reduced axial force N_{mean}^* , in which W.D.1 and W.D.2 represent the wind direction ranges of $\theta = 0^\circ$ - 45° and 45° - 90° , respectively. When the value of $|N_{\text{mean}}^*|$ is small, G_f generally exhibits a large value. However, as $|N_{\text{mean}}^*|$ increases, the values of G_f collapse into a narrow range around $G_f = 2.0$, which correspond to a peak factor of $g_f \approx 2.5$, based on the quasi-steady assumption, i.e., $G_f \approx (1 + g_f \times I_{uH})^2 = (1 + 2.5 \times 0.17)^2$. The value of $g_f \approx 2.5$ is somewhat

Fig. 6 Gust effect factor based on the load effect.

smaller than that for gable, troughed and mono-sloped roofs, which is approximately 3.0 [6]. This difference may be due to the effect of flow separation from the leading edges of the roof on the wind loads. That is, the turbulence induced by the flow separation seems lower for H.P. roofs than for the other roofs. In the following sections, the value of $G_f = 2.0$ is used for evaluating the design wind force coefficients, providing the equivalent static wind loads.

4.2 Design Wind Force Coefficients for Roofs with No Slope

For the purpose of simplicity, the design wind force coefficients on the roof are specified by two uniformly distributed values, C_{NW}^* and C_{NL}^* , over the windward and leeward halves (Fig. 7). Such a definition is the same as that used in the AS/NZ Standard [1]. The wind force coefficients can be evaluated based on the following procedure that was proposed by Uematsu et al. [6] for gable, troughed and mono-sloped roofs.

Step 1: The basic values of C_{NW}^* and C_{NL}^* , denoted

Fig. 7 Roof division for the specification of wind force coefficients.

as C_{NW0} and C_{NL0} , are determined from a combination of the lift coefficient (C_L) and the moment coefficient (C_{My} or C_{Mx}) that produces the maximum load effect when $\theta = 0^\circ$ or 90° . The C_{NW0} and C_{NL0} values may be given by the following equations [6, 14, 15]:

$$\theta = 0^\circ: C_{NW0} = -C_L - 2C_{My} \quad (4)$$

$$C_{NL0} = -C_L + 2C_{My} \quad (5)$$

$$\theta = 90^\circ: C_{NW0} = -C_L + 2C_{Mx} \quad (6)$$

$$C_{NL0} = -C_L - 2C_{Mx} \quad (7)$$

Step 2: Considering that the axial force induced in the column may become the maximum for an oblique wind, a correction factor γ is introduced: γ is defined as the ratio of the actual peak force for a wind direction range of $\theta = 0^\circ$ to 45° (W.D.1) or $\theta = 45^\circ$ to 90° (W.D.2) to that computed from the C_{NW0} and C_{NL0} values for $\theta = 0^\circ$ or 90° . Indeed, the value of γ ranges from 1.0 to 1.2 in most cases. When the calculated value of γ is less than 1.0, it is replaced by 1.0.

Step 3: The design wind force coefficients, C_{NW}^* and C_{NL}^* , which give the equivalent static wind loads, are provided by the following equations:

$$C_{NW}^* = \frac{\gamma C_{NW0}}{G_f} \quad (8)$$

$$C_{NL}^* = \frac{\gamma C_{NL0}}{G_f} \quad (9)$$

The most important problem for specifying the design wind force coefficients is how to combine the values of C_L and C_{My} in Eqs. (4) and (5) and C_L and C_{Mx} in Eqs. (6) and (7). The wind force coefficients C_{NW0} and C_{NL0} should be determined so that they produce the maximum load effect. Fig. 8a shows a phase-plane representation of the C_{My} - C_L relation for $h/a = 1/3$ when $\theta = 0^\circ$. There exists a positive correlation

Fig. 8 Phase-plane representation of the C_{My} - C_L relation for a solid roof ($h/a = 1/3$, $\theta = 0^\circ$): (a) experimental result; (b) model of the envelope of the trajectory.

Fig. 9 Wind force coefficients C_{NW}^* and C_{NL}^* (W.D.1): (a) C_{NW}^* ; (b) C_{NL}^* .

between these two coefficients. The correlation becomes poorer as the h/a ratio increases. Envelop of the C_{My} - C_L trajectory is approximated by a hexagon, as shown in Fig. 8b. The critical condition that produces the maximum load effect may be given by a combination of C_L and C_{My} at one of these six apexes. In order to investigate the load combination effects, the axial forces induced in the columns were computed for the six combinations of C_L and C_{My} (Apexes 1-6). Focus is on the two Load Cases A and B, producing the maximum tension and compression in the columns, respectively. Substituting the corresponding C_L and C_{My} values into Eqs. (4) and (5), the values of C_{NW0} and C_{NL0} for each load case are obtained. The same procedure is taken for $\theta = 90^\circ$, in which C_L and C_{Mx} are considered.

The results of C_{NW}^* and C_{NL}^* for W.D.1 and W.D.2

are shown in Figs. 9 and 10, respectively. In the figures, the specified values in the AS/NZ Standard [1] are also shown. The standard provides two values of wind force coefficients (expressed as “positive” and “negative”) for each of the windward and leeward halves. The range of h/a is limited from 0.1 to 0.3. The proposed wind force coefficients, C_{NW}^* and C_{NL}^* , do not necessarily agree with the AS/NZ specifications, although a good agreement can be seen for some cases. Similar features were observed for gable, troughed and mono-sloped roofs in the authors’ previous study [6]. Such a difference may be due to a difference in the criteria for specifying the wind force coefficients.

Next, the axial forces induced in the columns were computed by using C_{NW}^* and C_{NL}^* and compared with those predicted from the AS/NZ specifications. Fig. 11

Fig. 10 Wind force coefficients C_{NW}^* and C_{NL}^* (W.D.2): (a) C_{NW}^* ; (b) C_{NL}^* .

Fig. 11 Reduced axial forces induced in the columns: (a) W.D.1; (b) W.D.2.

shows the results, in which the ordinate is the non-dimensional axial force N^* divided by G_f . As mentioned above, the AS/NZ Standard generally provides four combinations of the wind force coefficients on the windward and leeward halves. The maximum and minimum axial forces among them are shown Fig. 11. It is interesting to note that these values are consistent with the present results for Load Cases A and B for $h/a = 0.1$ to 0.3 , despite a difference in the wind force coefficients, as shown in Figs. 9 and 10.

4.3 Effect of Roof Slope on Wind Force Coefficients

The wind force coefficients C_{NW}^* and C_{NL}^* for $\beta_x > 0^\circ$ were also obtained through the above-mentioned procedure. Because the roof is not symmetric with respect to the x -axis, the wind direction range W.D.1 should be $\theta = -45^\circ$ to 45° . Furthermore, another wind

direction range of $\theta = -45^\circ$ to -90° (W.D.3) should be considered. The results on C_{NW}^* and C_{NL}^* for these wind direction ranges are plotted in Figs. 12-14. As might be expected from the results in Fig. 5, the values of C_{NW}^* and C_{NL}^* generally increase in magnitude with increasing β_x up to about 20° for W.D.1 and W.D.2. Some coefficients further increase and the others decrease in magnitude with increasing β_x beyond 20° . The solid lines in the figures show the simplified models for C_{NW}^* and C_{NL}^* as a function of β_x , which can be used for the design of H.P. free roofs.

5. Conclusions

The wind force coefficients for designing the structural frames of hyperbolic paraboloid free roofs were proposed based on a wind tunnel experiment with rigid models made of nylon resin by using laser

Fig. 12 Effect of β_x on C_{NW}^* and C_{NL}^* ($h/a = 1/2$, W.D.1): (a) C_{NW}^* ; (b) C_{NL}^* .

Fig. 13 Effect of β_x on C_{NW}^* and C_{NL}^* ($h/a = 1/2$, W.D.2): (a) C_{NW}^* ; (b) C_{NL}^* .

Fig. 14 Effect of β_x on C_{NW}^* and C_{NL}^* ($h/a = 1/2$, W.D.3): (a) C_{NW}^* ; (b) C_{NL}^* .

lithography. The overall aerodynamic forces and moments acting on the roofs with $h/a = 1/2$, $1/3$ and $1/6$ were measured with a six-component force balance in a turbulent boundary layer. The roof slope β_x , obtained by raising one of the higher corners and lowering the opposite corner, was changed from 0° to 40° . The effects of h/a and β_x on the aerodynamic forces and

moments were investigated.

Based on the results, the design wind force coefficients were discussed from the viewpoint of load effect. The axial forces induced in the columns were regarded as the load effect for discussing the design wind loads, assuming that the roof was rigid and simply supported by four corner columns. The design

wind force coefficients, represented as uniformly distributed values on the windward and leeward halves of the roof, were proposed as a function of h/a and β_x .

In the membrane roof case, the deformation and oscillation may affect the wind loads. Furthermore, the other roof supporting systems different from that considered here may be used in practical designs, e.g., “post and guy cable” system. The application of the wind force coefficients proposed in the present paper to such cases should be investigated. These are the subjects of future studies.

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References

- [1] Standards Australia, Australia/New Zealand Standard, AS/NZ 1170.2, 2011.
- [2] A.J. Dutt, Wind loading on a pyramidal roof structure, *International Journal of Space Structures* 1 (1985) 105-110.
- [3] A.J. Dutt, Wind pressure distribution on multiple hyperbolic paraboloid shell roof building, *International Journal of Space Structures* 2 (1986) 49-54.
- [4] A.J. Dutt, Wind loading on a “saw tooth” multiple hyperbolic paraboloid shell roof, *International Journal of Space Structures* 3 (1988) 43-50.
- [5] Y. Uematsu, T. Stathopoulos, Wind loads on free-standing canopy roofs: A review, *Journal of Wind Engineering, JAWE (Japan Association for Wind Engineering)* 95 (2003) 245-256.
- [6] Y. Uematsu, E. Iizumi, T. Stathopoulos, Wind force coefficients for designing free-standing canopy roofs, *Journal of Wind Engineering and Industrial Aerodynamics* 95 (2007) 1486-1510.
- [7] J. Beutler, Beitrag zur statischen windbelastung von seilnetzwerken—Ergebnisse von windkanaluntersuchungen, hanging roofs (Colloquium on hanging roofs, continuous metallic shell roofs and superficial lattice roofs), in: *Proceedings of the IASS (International Association for Shell and Spatial Structures) Colloquium on Hanging Roofs, Continuous Metallic Shell Roofs and Superficial Lattice Roofs*, Paris, North-Holland Publishing Company, 1963, pp. 76-86.
- [8] P.K.F. Pun, C.W. Letchford, Analysis of a tension membrane hyper roof subjected to fluctuating wind loads, in: *Proceedings of Third Asia-Pacific Symposium on Wind Engineering*, Hong Kong, 1993, pp. 741-746.
- [9] T. Kaseya, A. Okada, N. Miyasato, S. Hiroishi, Y. Nagai, S. Yoshino, et al., Study on wind response on H.P.-shaped membrane roof, Part 1: Effect of Reynolds number on wind pressure distribution, in: *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan*, 2013, pp. 181-182. (in Japanese)
- [10] R. Nakagawa, A. Okada, N. Miyasato, S. Hiroishi, Y. Nagai, S. Yoshino, et al., Study on wind response on H.P.-shaped membrane roof, Part 2: Effect of Reynolds number on static and dynamic response, in: *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan*, 2013, pp. 183-184. (in Japanese)
- [11] S.J. Gumley, Panel Loading Mean Pressure Study for Canopy Roofs, OUEL report No.1380/81, Department of Engineering Science, University of Oxford, 1981.
- [12] B. Natalini, J.O. Marighetti, M.B. Natalini, Wind tunnel modelling of mean pressures on planar canopy roof, *Journal of Wind Engineering and Industrial Aerodynamics* 90 (2002) 423-439.
- [13] F. Takeda, T. Yoshino, Y. Uematsu, Wind Force Coefficients for the Design of Hyperbolic Paraboloid Shaped Free Roofs, Research reports on membrane structures 2012, The Membrane Structures Association of Japan, 2013, pp. 79-92. (in Japanese)
- [14] Y. Uematsu, F. Arakatsu, S. Matsumoto, F. Takeda, Wind force coefficients for the design of hyperbolic paraboloid free roof, in: *Proceedings of the Seventh Asia-Pacific Conference on Wind Engineering*, Taipei, Taiwan, 2009. (CD-ROM)
- [15] Y. Uematsu, Y. Miyamoto, H. Sakurai, E. Gavanski, Wind Force Coefficient for Designing Porous Canopy Roofs, Part 2: H.P.-Shaped Roof, Research reports on membrane structures 2012, The Membrane Structures Association of Japan, 2013, pp. 71-78. (in Japanese)
- [16] F. Takeda, T. Yoshino, Y. Uematsu, Wind force coefficients for the design of a hyperbolic paraboloid free roof, in: *Proceeding of the IASS (International Association for Shell and Spatial Structures) Symposium*, Shanghai, China, 2010, pp. 1698-1709.