Wind Engineering Joint Usage/Research Center
FY2021 Research Result Report

Research Field: Wind Hazard Mitigation/Wind Resistant design
Research Year: FY2021
Research Number: 21213002
Research Theme: Aerodynamic characteristic of retractable dome roofs with various rise-span ratios

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Budget [FY2021]: 400,000Yen

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*Figures can be included to the report and they can also be colored.
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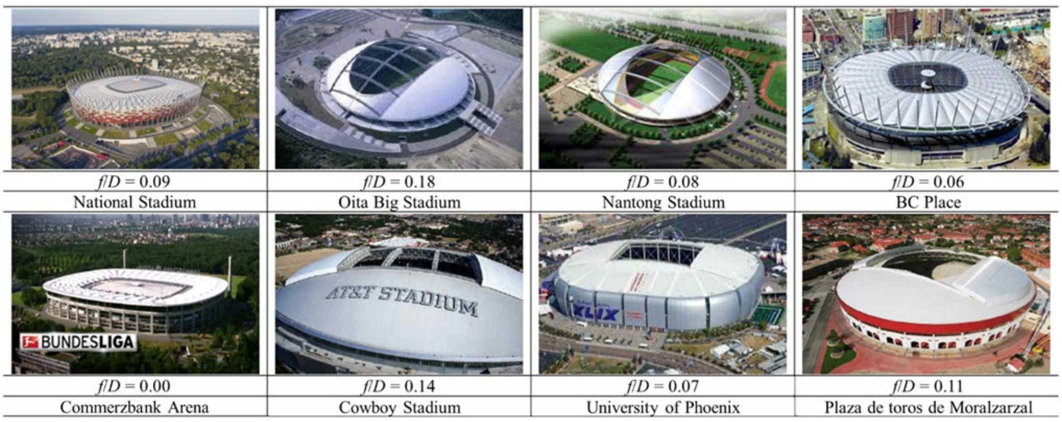
1. Research Aim

There are relatively less researches on wind load for retractable dome roofs than general dome roofs, and the codes of wind load did not established yet as well. Therefore, a research has been published with the contents of wind pressure analysis, comparison and proposal of standards for retractable dome roofs through wind tunnel experiment since 2017. The research so far has been executed that focusing on the shape of plan, retractable type, opening ratio and height-span ratio (Hereafter called as H/D). But according to previous researches rise-span ratio (Hereafter called f/D) 0.1 only has been considered. As shown in <Fig. 1>, the actual retractable dome roofs compose with various f/D. There have been researches for aerodynamic characteristic according to the changing of f/D in case of closed dome roof in many preceding researches. Among them, Uematsu et al. (1997) and Noguchi and Uematsu (2003) executed the experiments with various f/D and H/D targeting closed dome roof. As a result, the change of f/D highly affected on the change of wind pressure that applied to the roof, a negative pressure got increased when f/D is low and positive pressure got increased as well when f/D is high. Based on results above, it is possible to expect the change of f/D has a high influence on the changing of wind pressure in case of retractable dome roofs also. Therefore, this study aims to analyze the wind pressure characteristics of the retractable dome roof according to the change of f/D.

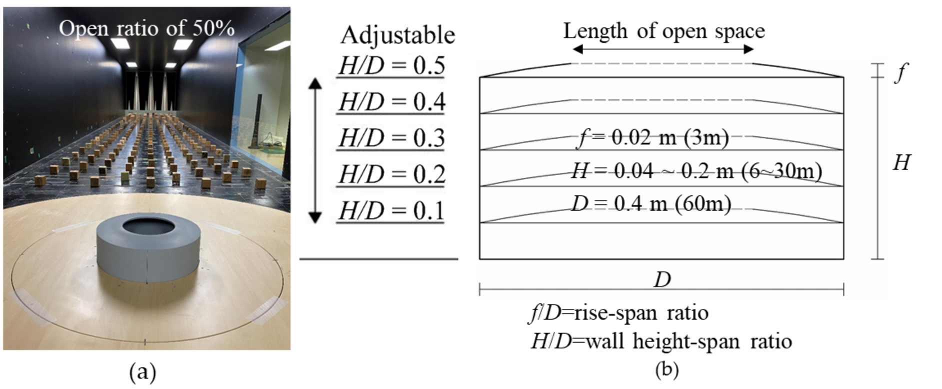


< Fig. 1> Various rise-span ratios of retractable dome roofs

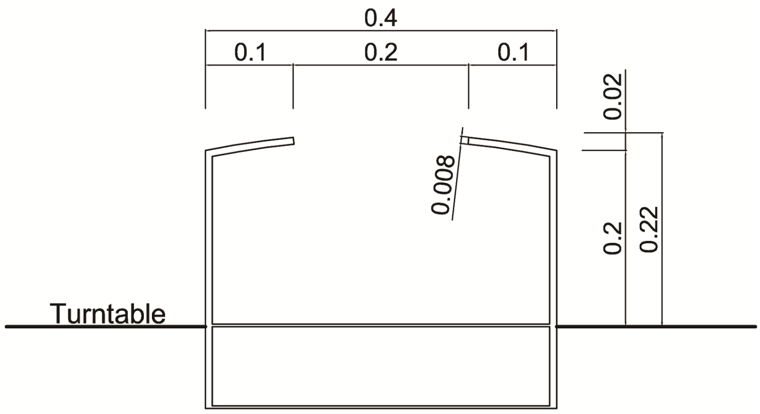
2. Research Method

2.1 model

As shown in <Fig. 2a>, the model used in the experiment simulated a spherical dome with an opening. <Fig. 2b> shows a section of the model, where *f*, *H*, and *D* denote the rise in the dome roof, wall height, and span length, respectively. In this study, a length scale of 1/150 was used. The values of *f*, *H*, and *D* were 0.02 m, 0.04–0.2 m, and 0.4 m, respectively; these values are shown in <Fig. 3>and Table 1. *H* was adjusted by 0.04 m by using a turntable with adjustable heights to conduct the test. The opening ratio is defined as the ratio of the span length (*D*) of the model and diameter of the open space, which are 0.4 m and 0.2 m, respectively. Therefore, the opening ratio is 50%. The specifications of the model are listed in Table 1.



< Fig. 2> Test model



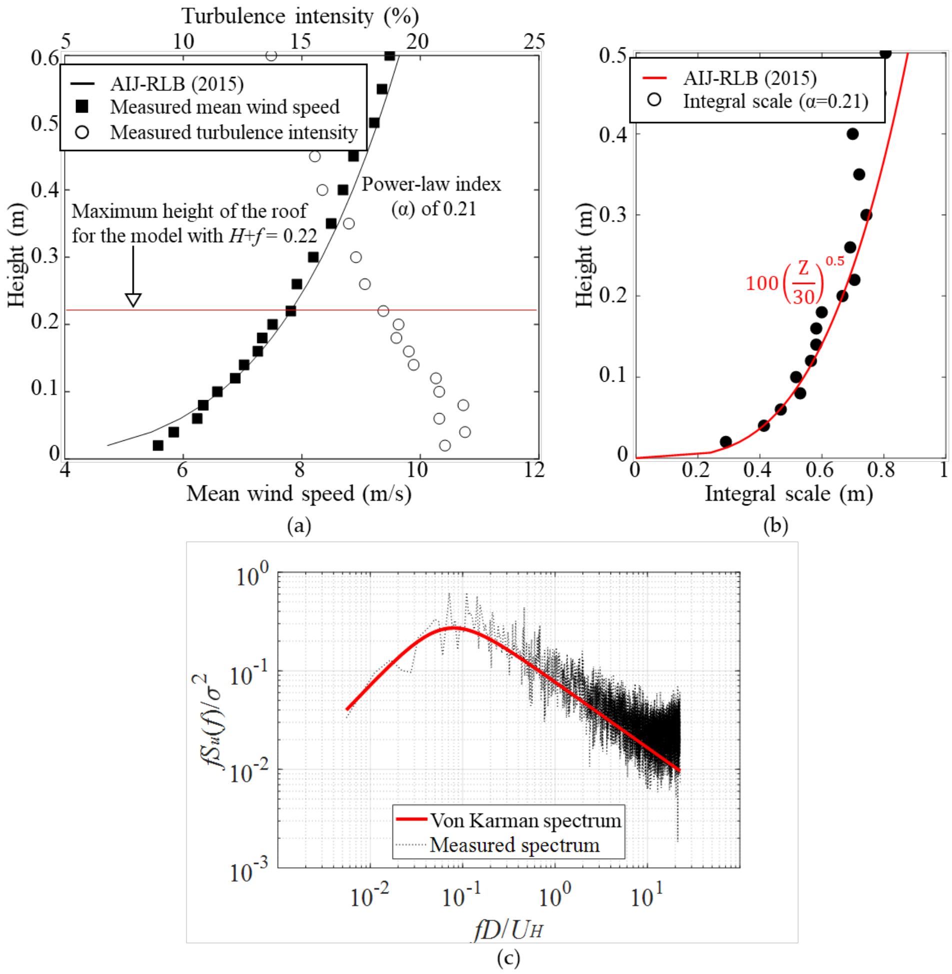
< Fig. 3> Detailed dimensions of model (in meters).

Table 1. Model dimensions.

f (in full scale, m)	*H* (in full scale, m)	*D* (in full scale, m)	*f*/*D*	*H*/*D*
	0.04 (6)			0.1
	0.08 (12)			0.2
0.02 (3)	0.12 (18)	0.4 (60)	0.05	0.3
	0.16 (24)			0.4
	0.2 (30)			0.5

2.2 Characteristics of Approaching Oncoming Flow and Data Acquisition

The oncoming flow was simulated according to the conditions proposed in the Japanese Recommendations for Loads on Buildings (AIJ-RLB). An urban topography was assumed, and the targeted power law exponent (α) of the mean wind speed profile was set to be 0.21. The mean wind speed and turbulence intensity profiles are shown in <Fig. 4a>. The turbulent boundary layers were reproduced using various spires and roughness blocks. Assuming a wind speed scale of 1/3, for the maximum height of the roof of the model with *H/D* = 0.5, the mean wind speed was 7.8 m/s, and the turbulence intensity was 19.1%. <Fig. 4b> shows the integral scales of the simulated flow, which gradually increased when the height increased. In addition, the integral values (solid line in Fig. 4b) calculated using AIJ-RLB are in good agreement with the relationship between the simulated integral scales and AIJ-RLB values. The power spectrum of the longitudinal wind velocity fluctuation is consistent with the target von Karman spectrum, as shown in <Fig. 4c>.

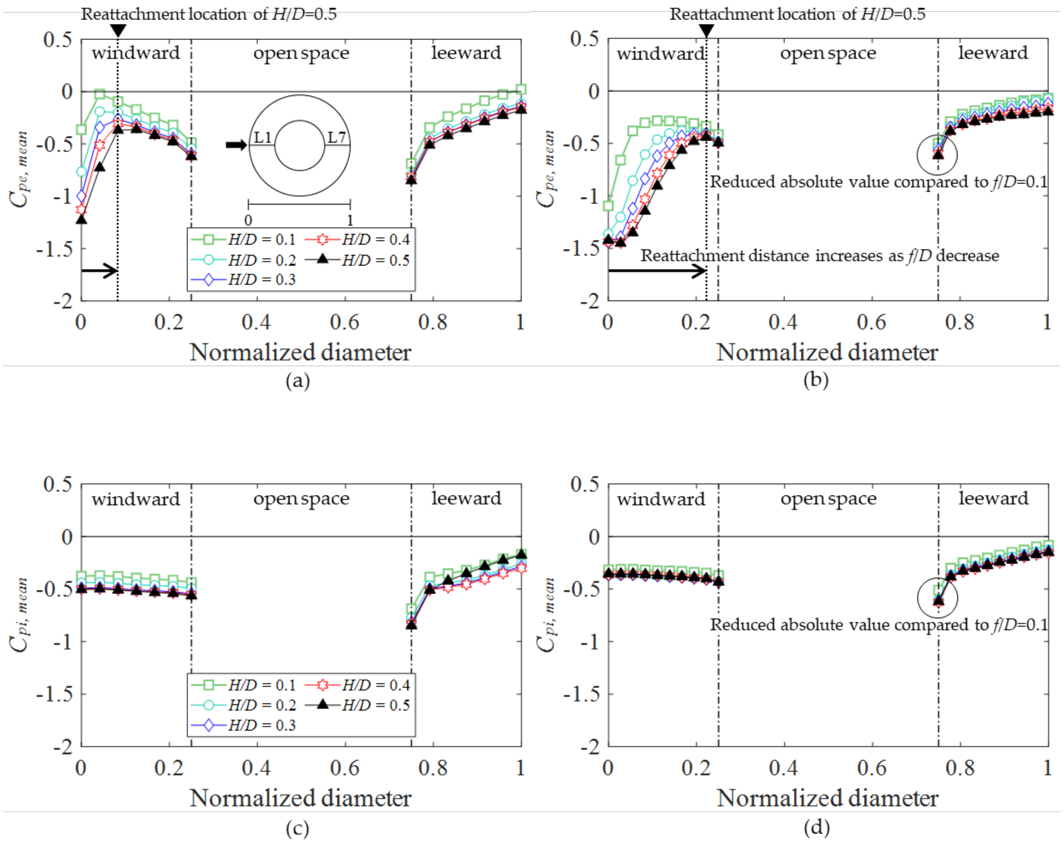


<Fig. 4> Characteristics of oncoming flow: (a) Mean velocity and turbulence intensity profiles; (b) Profile of integral scale; (c) Power spectra of velocity fluctuation at H = 0.22 m.

3. Research Result

3.1 Comparison of Mean Pressure Coefficients

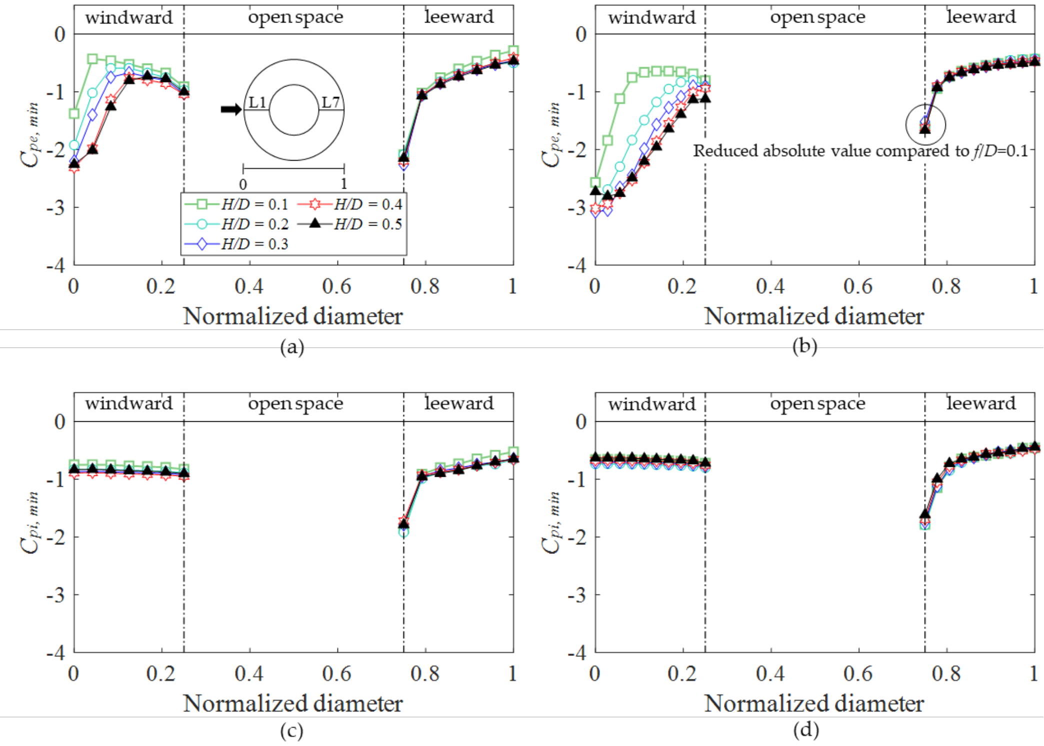
<Fig. 5> shows the mean pressure coefficients for the two *f/D* cases. The x-axis represents the normalized diameter, which is defined as the ratio of the pressure tap distance from the roof edge of the windward side to the roof edge of the leeward side. Thus, a normalized diameter of 0 indicates the roof edge of the windward region, and a normalized diameter of 1 indicates the roof edge of the leeward region. In both cases, the negative pressure was dominant. <Fig. 5a and b> show the external mean pressure coefficients ($C_{pe,mean}$). In the windward region, the absolute value increased in both cases, and the absolute value was larger when *f/D* = 0.05. This occurred because as *f/D* decreased, the reattachment distance increased and a relatively large vortex was formed. In the leeward region, the overall absolute values showed similar values and variations regardless of the change in *H/D* in both cases. This occurred because the characteristics of the deviated flow became similar owing to the boundary layer that formed on the roof surface after reattachment. Comparing the two cases, the absolute value based on *f/D* = 0.05 was slightly smaller at the normalized diameter of 0.75 as it was affected by the separation of the deviated flow. <Fig. 5c and d> show the internal mean pressure coefficients. The absolute value for *f/D* = 0.05 was slightly smaller than that for *f/D* = 0.1, although the difference was insignificant and similar variations were indicated in general.



<Fig. 5> External and internal mean pressure coefficients based on *f/D*: (a) $C_{pe,mean}$ of f/D = 0.1; (b) $C_{pe,mean}$ of *f/D* = 0.05; (c) $C_{pi,mean}$ of f/D = 0.1; (d) $C_{pi,mean}$ of *f/D* = 0.05.

3.2 Comparison of Negative Peak Pressure Coefficients

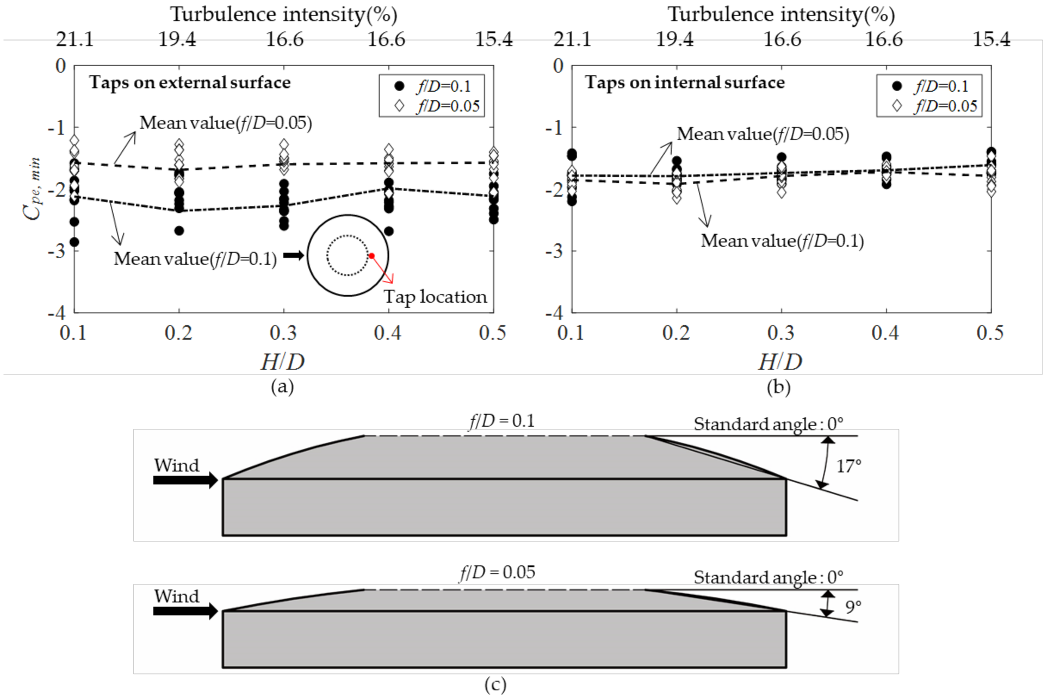
<Fig. 6> shows the negative peak pressure coefficients for the two *f/D* cases. As described above, the trend of the absolute value change for different *f/D* and H/D values was similar. However, in the case involving the negative external peak pressure coefficients ($C_{pe,min}$) shown in <Fig. 6b>, the absolute value at the normalized diameter of 0.75 was smaller than that for *f/D* = 0.1. In the case involving the negative internal peak pressure coefficients ($C_{pi,min}$) shown in <Fig. 6c and d>, both cases exhibited similar absolute values and variations.



<Fig. 6> External negative peak pressure coefficient based on *f/D*: (a) $C_{pe,min}$ of *f/D* = 0.1; (b) $C_{pe,min}$ of *f/D* = 0.05 (c) $C_{pi,min}$ of *f/D* = 0.1; (d) $C_{pi,min}$ of *f/D* = 0.05.

<Fig. 7a and b> show the negative external and internal peak pressure coefficients ($C_{pe,min}$ and $C_{pi,min}$) on the two external and internal taps of the roof edge of the open space affected by separation, respectively. The x-axis represents the *H/D* ratio and turbulence intensity values for each *H/D*. In the figures, the markers indicate the value for each of the 10 samples, and the dotted line indicates the mean of the 10 sample values for each *f/D*. The absolute values for each case were similar regardless of the *H/D* and turbulence intensity changes. This is because the flow characteristics were similar owing to the boundary layer formed on the roof surface after reattachment. As shown in <Fig. 7a>, the absolute value of *f/D* = 0.1 for the external tap was greater than that for *f/D* = 0.05; however, the absolute value of the roof internal pressure tap was similar for both cases. This is because the roof had a different shape. <Fig. 7c> shows the inclination angle of the roof. Based on the external roof of the leeward region, it was observed that the larger the *f/D*, the higher the inclination angle of the roof. As mentioned earlier, the negative external peak pressure coefficient for *f/D* = 0.1 was larger than that for *f/D* = 0.05. This is

because the space in which the vortex formed after separation increased with f/D.

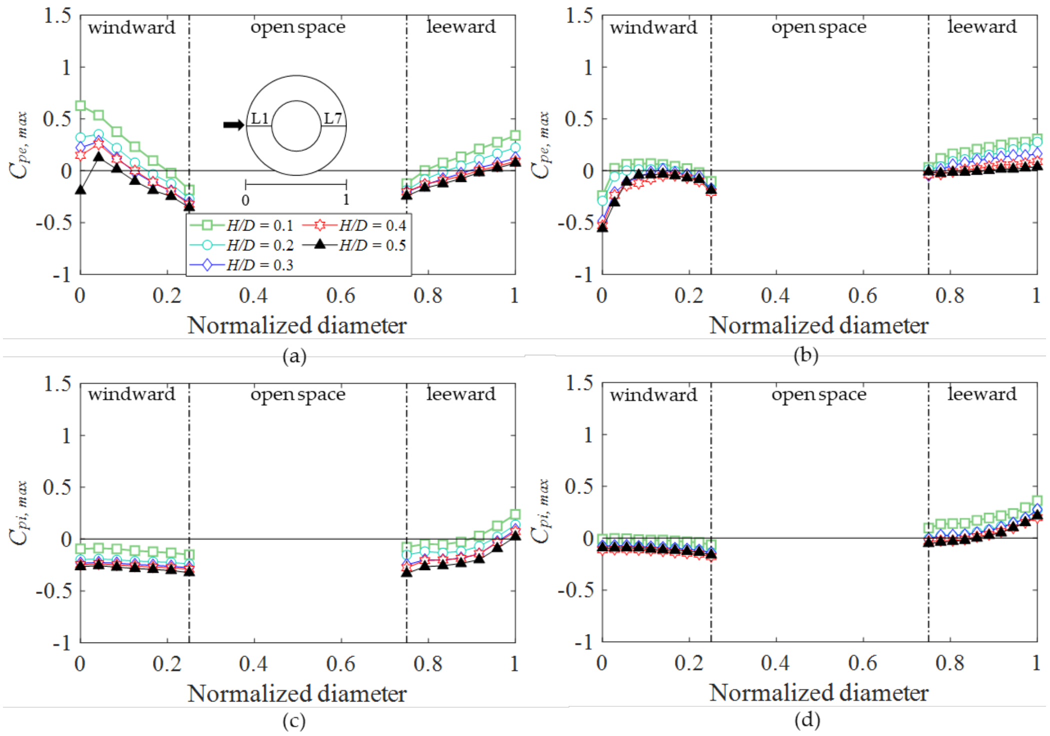


<Fig. 7> $C_{pe,\ min}$ and $C_{pi,\ min}$ based on turbulence intensity: (a) $C_{pe,\ min}$ on external surface of roof; (b) $C_{pi,\ min}$ on internal surface of roof; (c) Inclination angle of leeward-side roof.

3.3 Comparison of Positive Peak Pressure Coefficients

<Fig. 8> shows the positive peak pressure coefficients for the two f/D cases. The positive peak net pressure coefficient was defined as the mean of the maximum values of C_{pe} and C_{pi} measured in the ten samples. However, a negative pressure value was observed in some regions. These regions were dominated by the separation and boundary layer effects formed on the dome surface, resulting in no positive pressure. <Fig. 8a and b> show the positive external peak pressure coefficient (Cpe,max). For the positive external peak pressure coefficient shown in <Fig. 8a>, the absolute value when f/D = 0.1 was greater than that when f/D = 0.05 owing to the effect of the roof rise. As the rise of the dome roof increased, the reattachment distance decreased and was affected intermittently by the oncoming flow. Hence, the absolute value for f/D = 0.1 was relatively large. Meanwhile, as H/D increased, the absolute value decreased. In the case of f/D = 0.05 shown in <Fig. 8b>, the negative pressure was dominant because of the low rise-span ratio; therefore, the effect of the positive pressure was insignificant and the absolute values were similar regardless of H/D. <Fig. 8c and d> show the positive internal peak pressure coefficients ($C_{pi,max}$). In the windward region, the negative pressure was dominant in both cases; therefore, the effect of the positive pressure was insignificant. In contrast, the whole or part regions were influenced by the positive pressure for both cases in the leeward region. This was caused by the pressure recovery phenomenon. In the case of f/D = 0.1, the normalized diameters ranging from 0.85 to 1 were influenced by the positive pressure. In the case of f/D = 0.5, the whole surface of the roof was influenced by the positive pressure. In addition, the absolute values in both cases were largest when the normalized

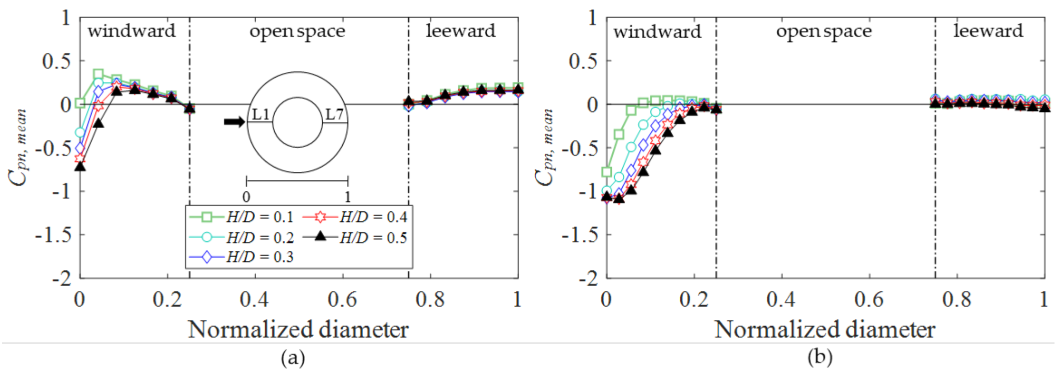
diameter was 1.



<Fig. 8> External positive peak pressure coefficient based on *f/D*: (a) $C_{pe,max}$ of *f/D* = 0.1; (b) $C_{pe,max}$ of *f/D* = 0.05; (c) $C_{pi,max}$ of *f/D* = 0.1; (d) $C_{pi,max}$ of *f/D* = 0.05.

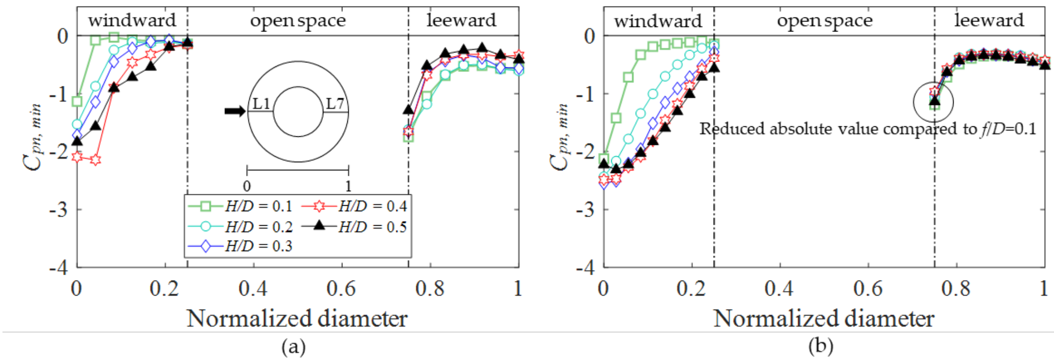
3.4 Comparison of Net Pressure Coefficients

<Fig. 9> shows the mean net pressure coefficients ($C_{pn,mean}$) for the two *f/D* cases. In <Fig. 9a>, the absolute value of the windward region for *f/D* = 0.1 was more affected by the positive pressure than for *f/D* = 0.05. This was caused by the direct effects of the oncoming flow and constant negative pressure on the internal surface of the roof. The absolute value for *f/D* = 0.1 in the leeward region was also larger compared to that for *f/D* = 0.05. This is why the effects of the positive pressure on the external surface at this point were more significant than those on the internal surface in the case of *f/D* = 0.1, whereas the pressures at the external and internal surfaces of the roof were similar.



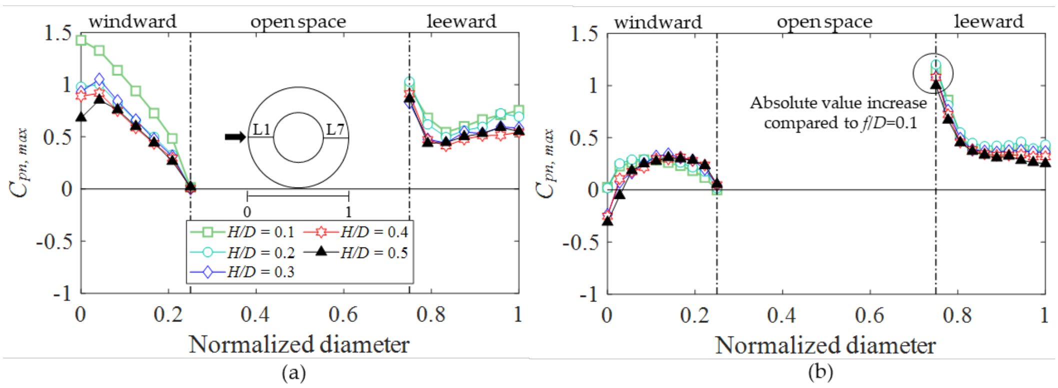
<Fig. 9> Mean net pressure coefficient based on *f/D*: (a) $C_{pn,mean}$ of *f/D* = 0.1; (b) $C_{pn,mean}$ of *f/D* = 0.05.

<Fig. 10> shows the negative peak net pressure coefficients ($C_{pn,min}$) for the two f/D cases. Compared with the case of f/D = 0.05, the absolute value was smaller in the windward region and larger in the leeward region for f/D = 0.1. This phenomenon is associated with the vortex on the external roof surface and constant negative pressure on the internal surface of the roof. In both cases, the wind pressures on the internal roof surface exhibited similar values and variations. Owing to the relatively high roof rise, the vortex current caused by separation in the windward region was small. In contrast, the vortex current generated by the separation in the leeward region was larger owing to the increase in the roof inclination angle. Therefore, the absolute values for each region were different.



<Fig. 10> Negative net pressure coefficient based on f/D: (a) $C_{pn,min}$ of f/D = 0.1; (b) $C_{pn,min}$ of f/D = 0.05.

<Fig. 11> shows the positive peak net pressure coefficients ($C_{pn,max}$) for the two f/D cases. Compared with the case of f/D = 0.05, the absolute value was larger in the windward region and smaller in the leeward region for f/D = 0.1. In the windward region, the absolute value was larger than that for f/D = 0.05 owing to the direct effect of the incoming flow on the external roof surface. However, the leeward region indicated a larger roof inclination angle, resulting in a smaller absolute value at a normalized diameter of 0.75 owing to the relatively larger vortex formed in the external roof surface relative to that in the internal roof surface. However, the absolute value for f/D = 0.1 was significantly large when the normalized diameter was over 0.8. As previously mentioned, this was why the effects of the positive pressure on the external surface at point were more significant than those on the internal surface in the case of f/D = 0.1, although the pressures at the external and internal surfaces of the roof were similar.



<Fig. 11> Positive peak net pressure coefficient based on *f/D*: (a) $C_{pn,max}$ of *f/D* = 0.1; (b) $C_{pn,max}$ of *f/D* = 0.05.

3.5 Conclusions

In this study, the external, internal, and net pressure characteristics of open-dome roofs with low span-rise ratios (*f/D* = 0.05) and openings were analyzed via wind tunnel experiments. The findings were compared with those of previous studies to discuss the characteristics of wind pressures varying with the roof shape (i.e., opening, *f/D*, and *H/D*). The primary conclusions of this study are as follows:

(1) In the windward region of the external roof surface, both the *f/D* = 0.1 and *f/D* = 0.5 cases were dominated by the negative pressure induced by the separation of the approaching airflow, where the effect of the negative pressure increased with *H/D*.

(2) In the leeward region of the external roof surface, the effect of the negative pressure in the roof edge region of the open space was increased by the separation of the flow deviating from the windward roof owing to the opening located in the center in both *f/D* cases.

(3) The negative pressure was dominant in all areas of the internal roof surface, including the leeward region. The negative pressure in the roof edge region of the open space was increased by the separation of the flow deviating from the windward region owing to the opening located at the center, similar to the case of the external roof surface. However, similar values were obtained regardless of the changes in the values of *f/D* and *H/D*.

(4) For the net pressure, the reattachment distance of the windward region increased as the rise-span ratio increased, resulting in an increase in the negative net pressure and a decrease in the positive net pressure owing to a relatively large vortex. In contrast, the roof inclination angle of the leeward region decreased as the rise-span ratio decreased, resulting in a decrease in the negative net pressure and an increase in the positive net pressure owing to a relatively small vortex at the roof edge of the open space in the leeward region.

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

1. Park, MJ., Yoon, SW., Kim, YC., Cheon, DJ., Wind Pressure Characteristics Based on the Rise-Span Ratio of Spherical Domes with Openings on the Roof, *Buildings 2022* (in press).

[Presentations at academic societies]

1. 2021 年度 東京工芸大学 風工学研究拠点 共同利用・共同研究 研究集会のご案内, 強風防災・耐風構造分野

[Published books]

1.

[Other]

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5. Research Group

1. Representative Researcher

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2. Collaborate Researchers

   Professor Yong Chul, Kim

   Ph.D. student Jong Ho, Lee

   Ph.D. student Dong Jin, Cheon

6. Abstract (half page)

Research Theme

Aerodynamic characteristic of retractable dome roofs with various rise-span ratios

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Summary・Figures

Wind loads are a primary concern in dome-roof structures with openings such as retractable dome roofs. This is because the openings can cause damage to the cladding owing to high internal pressure. In this study, the wind pressure characteristics of a dome with an opening that varied based on the opening, rise-span ratio, and height span were examined by comparing the results from wind tunnel tests with those from previous studies. The negative pressure dominated the internal pressure of the roof in all regions and was not significantly affected by changes in the rise-span and height-span ratios. The reattachment distance of the windward region increased as the rise-span ratio increased, increasing the negative net pressure and decreasing the positive net pressure owing to a relatively large vortex. The roof inclination angle of the leeward region decreased as the rise-span ratio decreased, resulting in a decrease in the negative net pressure and an increase in the positive net pressure owing to a relatively small vortex.