Wind pressure characteristics of elliptical retractable dome roofs

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ABSTRACT
This study investigated the wind pressure characteristics of an elliptical plan retractable dome roof. Wind tunnel experiments were performed on elliptical dome roofs with varying wall height-to-span ratios (0.1–0.5) and opening ratios (0, 10, 30, and 50%), where the opening ratio was defined as the ratio of the open area of the roof to the total area of the roof. The resulting peak pressure coefficients of the closed dome roof were then compared with those of the Japanese wind load code (AIJ-RLB (2015)) as there are no current peak pressure coefficients for the cladding design code of elliptical dome roofs. The resulting peak pressure coefficients for each elliptical retractable dome roof opening ratio were also compared with those for the cladding design of spherical retractable domes proposed in previous research. Based on the results of the comparative analysis, negative and positive peak pressure coefficients were proposed for the cladding design of elliptical retractable dome roofs.

1. Introduction
With the rising demand for leisure and sports activities, the number of retractable dome roofs is increasing worldwide. Retractable dome roof structures can operate in open, partially open, and closed states and are therefore relatively freer from seasonal and weather constraints compared to closed roofs, which make them popular features across the world. Most dome roofs, being light and flexible, are constructed using thin metals and/or membranes. However, this leads to the roofs being sensitive to wind loads under which they can be easily torn or destroyed. Dome structures around the world have suffered damages caused by wind loads, e.g., the Jeju Soccer Field in South Korea, the Louisiana Superdome in Louisiana, USA, and the Olympic Stadium in Montreal, Canada. These incidents were mainly caused by failure to predict the loads on the cladding due to strong winds. Wind load is one of the most influential factors in the destruction of the cladding of buildings. Furthermore, the roofs of tall buildings as well as low-rise buildings are subject to strong local wind pressure that can lead to abnormalities in the cladding. For example, the large-span roof structure of a large space building is subjected to considerable local wind pressures. As a result, the design of a spatial retractable roof structure should consider the wind loads in all cases of its open and closed states. Because the complex geometric problems of a retractable roof have not been completely resolved (Masubuchi 2013), Cheon et al. (2018) analysed the external peak pressure coefficients for cladding design through a wind tunnel test on a spherical retractable dome roof and applied the analysis results to the current wind load code. As a result, in the case of a retractable roof, it was confirmed that the wind load code underestimated the external peak pressure coefficients at opening ratios of 30% and 50% compared to the test values.

Kim et al. (2019) conducted a wind tunnel test of a spherical retractable dome roof opening in the direction from the edge to the centre, with the wall height-to-span ratio (H/D) being increased in five steps from 0.1 to 0.5 for each opening ratio (0, 10, 30, and 50%) to obtain negative and positive peak pressure coefficients. The data were compared and analysed with the Japanese wind load code (AIJ-RLB (2015)), and the negative and positive peak pressure coefficients for the cladding design of a retractable dome roof were proposed.

Currently, the planes of most retractable dome roofs are constructed in spherical or elliptical shapes, but there have been relatively few studies on the external peak pressure coefficients for the cladding design of elliptical dome roofs compared to that of spherical dome roofs. In previous studies on elliptical dome roofs, the peak pressure was analysed to demonstrate the high efficiency of the elliptical shape among the circular and elliptical shapes of a hyperbolic paraboloid roof (Rizzo 2012; Rizzo and Ricciardelli 2017). However, because these prior studies investigated a hyperbolic paraboloid shape rather than a general dome roof shape, it has been difficult to apply their findings to the current wind load code, and the results are
applicable only to closed roof types. Thus, Lee et al. (2020) analysed the negative and positive peak pressure coefficients for the cladding design of a retractable elliptical dome roof and examined whether they could be applied to the current wind load code for designing elliptical dome roofs. The obtained peak pressure coefficients were compared with the coefficients defined in the Korean Building Code KBC 2016 (AIJ-RLB was applied mutatis mutandis). In consequence, the peak pressure coefficients obtained from the elliptical dome roof were found to be unsuitable for the current wind load code.

Therefore, in this study, the aerodynamic characteristics of an elliptical retractable dome roof were analysed through a wind tunnel test. For the closed roof state, negative and positive external peak pressures were analysed in comparison to KBC 2016, which is the current building code standard; for open roof states, the values were compared with the values proposed in Kim et al. (2019). Through the analysis, external peak pressure coefficients for cladding design suitable for elliptical retractable dome roofs were proposed.

2. Wind tunnel tests

A wind tunnel test was performed in a boundary-layer wind tunnel located at Tokyo Polytechnic University (TPU), Japan. Its working section was 1.8 m high by 2.2 m wide. Figure 1 outlines the wind tunnel test. Domes with a diameter D around a 72 m longitudinal axis and 48 m transverse axis, with a height of 0–30 m in full-scale were considered. Applying a length scale of 1/150, the test dome model consisted of a 0.48 m longitudinal axis, 0.32 m transverse axis, and height in the range of 0–0.2 m. The roof rise-to-span ratio was 0.1 with a height (H) of 0.04 m. The test was conducted under a total of ten wind directions from 0° to 90° in intervals of 10°, and for five different heights, varying H/D from 0.1 to 0.5 in intervals of 0.1.

The opening ratios of the dome roof model used in the tests were 0, 10, 30, and 50 %, and in this study, the opening ratio was defined as the ratio of the open area of the roof to the total area of the roof. External pressure taps on the model roof with the aforementioned opening ratios were installed in a specific order from the centre of the dome to the edge of the dome in a total of 12 lines (L1–L12) placed at 30° intervals. As the area of the roof decreases with the increase in the opening ratio of the roof model, the number of pressure taps gradually decreases accordingly. Only one internal pressure tap was installed per line inside the edge of the dome roof as installing the same number of internal pressure taps as external pressure taps would lead to an unrealistic roof thickness. A total of 205 internal and external pressure taps were installed in the model; 205 were used for an opening ratio of 0 %, 193 for 10 %, 157 for 30 %, and 121 for 50 % (Figure 2). All pressures were measured simultaneously using a multichannel pressure measurement system, and the tubing effects were numerically compensated using the transfer function and phase difference of the pressure measurement system with a cut-off frequency of 250 Hz, as shown in Figure 3.

For comparison with the current wind load code for a dome roof, the AIJ-RLB (2015) code was used with the proposed peak pressure coefficients for the cladding design of a spherical retractable dome roof performed in Kim et al. (2019). These coefficients were obtained under the same conditions as in this study: The velocity scale was 1/3, and the time scale was 1/50. Thus, an actual time of 10 min were 12 s in the wind tunnel. The moving averaging time was 1 s, and the coefficients were collected at a sampling frequency of 1000 Hz with low-pass filtering at a 300 Hz cut-off frequency, cascaded in each data acquisition channel. In addition, data correction was not considered because the maximum blockage ratio of the laboratory wind tunnel was less than 2 %. As for the oncoming flow simulation based on the conditions stipulated in AIJ-RLB (2015), spires, barriers, and roughness blocks were used to reproduce a = 0.30 (urban area) and a = 0.21 (semi-urban area) conditions. Figure 4 shows the mean wind speeds and turbulence intensities of the two oncoming flows simulated in the experiment. In Figure 4(a), for a = 0.30, the mean wind speed was 8.6 m/s and the turbulence intensity Iu was 20.7 % at a maximum height (H + h) of 0.24 m corresponding to model H/

![Figure 1](image-url)
For $\alpha = 0.21$, the mean wind speed was 9.1 m/s and the turbulence intensity $I_u$ was 17.3%.

Oncoming flows were determined by adjusting the wind speed in the wind tunnel to set the Reynolds number to obtain a stable peak pressure. As a result, the peak pressure was most stable at $Re = 2.2 \times 10^5$ for $\alpha = 0.30$ and $Re = 2.4 \times 10^5$ for $\alpha = 0.21$. This was similar to the Reynolds number determined in the research of Noguchi and Uematsu (2003), and a previous research by Letchford and Sarkar (2000) confirmed that the distribution of wind pressure was stable within a Reynolds number range from $2.3 \times 10^5$ to $4.6 \times 10^5$. Figure 4(b) shows the power spectra of wind velocity fluctuations for the two oncoming flows at the maximum model height of 0.24 m, which is in good agreement with the Karman spectra.
3. Results and discussion

The time histories of the external and internal pressure coefficients were calculated by
\[ C_p(t) = (P - P_{\text{pitot}})/q_{H+0.5f}, \]
where \( P \) is the pressure measured at each pressure tap, \( P_{\text{pitot}} \) is measured via a pitot tube installed 1.2 m above the wind tunnel floor, and \( q_{H+0.5f} \) is the velocity pressure at the mean roof height.

The peak pressure coefficients were defined as the negative and maximum values for each 10-min sample of \( C_p(t) \), and 10 ensemble averaged values were calculated for the external peak pressure coefficients to be applied in the cladding design. In the case of the extreme estimated using the Cook-Mayne method (Cook and Mayne 1980), where the peak values of 10 samples were used to calculate the mode and dispersion of the Fisher-Tippett (Type 1) distribution via the Best Linear Unbiased Estimator (BLUE) formulation (Lieblein 1974). When the 10 ensemble averaged value was compared with the extreme value obtained via the BLUE at the taps with the largest absolute value, the extreme value was observed to be approximately 10% larger, but the tendencies of variation in the absolute value were very similar. The current code (AIJ-RLB (2015)) employed in this study was for data obtained from 10 ensemble averaged values. Therefore, for a more accurate comparison, 10 ensemble averaged values were considered.

3.1. External peak pressure coefficients

In the case of an elliptical dome roof, the peak pressure varies according to the wind direction because the dome lengths in the longitudinal and transverse axis directions are different. Figure 5 depicts a graph showing the absolute value of the streamwise line for each

![Figure 5](image-url)
wind direction with the corresponding peak pressure coefficients. The $x$-axis represents the normalized diameter and the $y$-axis represents the negative and positive peak pressure coefficients. In this case, the normalized diameter 0 represents the leeward side of the dome, 0.5 the centre of the dome, and 1 the windward side of the dome. Additionally, $\theta_1$ represents L1 and L7 when the wind direction is 0°, $\theta_2$ represents L12 and L6 when the wind direction is 30°, $\theta_3$ represents L11 and L5 when the wind direction is 60°, and $\theta_4$ represents L10 and L4 when the wind direction is 90°. Figure 5(a) represents the peak pressure coefficients according to wind direction for the negative peak pressure coefficient on the roof surface, $C_{pe,min}$, under wind directions $\theta_1$–$\theta_4$. On the windward side, the difference in absolute value for each wind direction was small because the location of the separation on the roof wall was the same, but in the centre of the dome and on the leeward side, $\theta_4$ showed a larger absolute value than $\theta_1$. That is, the absolute value of the wind pressure coefficients tended to increase as the wind direction angle increased to 90°. Figure 5(b) shows the value of the positive peak pressure coefficient on the roof surface, $C_{pe,max}$, under wind directions $\theta_1$–$\theta_4$. The absolute value of $\theta_1$ was larger than that of $\theta_4$ in the centre of the dome and on the leeward side, but this difference was insignificant. Similar to the case of $C_{pe,min}$, the absolute value exhibited a decreasing tendency with an increase in the wind direction angle to 90°.

It was determined that when there are different longitudinal and transverse axes (as is the case with an elliptical dome roof, where the Reynolds number varies in proportion to the length in the axial direction), the boundary-layer formation changes according to the wind direction, resulting in different negative and positive peak pressures. In the current code, there is a limit to the largest absolute value for each region, but it is difficult to accurately identify the region from which the largest absolute value is derived for each wind direction in the case of an elliptical shape. Thus, in this study, the data were analysed according to the largest absolute value for each wind direction. In addition, the lines and wind directions with the largest absolute negative and positive peak pressure values were analysed.

3.1.1. External negative peak pressure coefficients on roof surface ($C_{pe,min}$)

Figure 6 shows the $C_{pe,min}$ of a closed roof for all $H/D$ values at $\alpha = 0.30$ and the distribution of $C_{pe,min}$ with varying opening ratios, and illustrates the tap lines where the largest absolute value appeared. The $x$-axis represents the normalized radius, and the $y$-axis represents $C_{pe,min}$. In this case, the normalized radius 0 of the $x$-axis is the centre of the dome, and 1 is the edge of the dome. Figure 6(a) shows the $C_{pe,min}$ at an opening ratio of 0 % for all $H/D$. The results of the analysis of the distribution of $C_{pe,min}$ show that most of the largest absolute values can be found at L12 under a wind

![Figure 6](image-url)

*Figure 6.* Variation of $C_{pe,min}$ depending on opening ratio for $\alpha = 0.30$: (a) opening ratio of 0 %, (b) 10 %, (c) 30 %, and (d) 50 %.
direction of 70–90° for all H/D. In other words, the largest absolute values tended to appear in the direction perpendicular to the wind direction. In addition, the absolute values on the windward side showed a rapid change due to separation around a normalized radius of 0.9 to 1. Subsequently, the abrupt change gradually decreased around a normalized radius of 0.8 (for H/D = 0.1, this change tended to decrease around a normalized radius of 0.9), so this region was defined as the reattachment region. After separation, the change slowed at a normalized radius of about 0.4. Figure 6(b) shows $C_{pe,min}$ at an opening ratio of 10%. The results of the analysis of the distribution of $C_{pe,min}$ indicate that the largest absolute values were most frequently found at L8 in the 80–90° wind direction for all H/D. Figure 6(c,d) show $C_{pe,min}$ at opening ratios of 30 % and 50 %, respectively.

As was the case for the opening ratio of 10 %, the largest absolute values for the opening ratios of 30 % and 50 % were mostly found at L8 in the 60–90° wind direction. The variations in $C_{pe,min}$ were similar for all opening ratios, indicating similar tendencies to those observed in a previous study by Cheon et al. (2018) on a circular roof. In addition, as the opening ratio increased, the differences in the absolute values of $C_{pe,min}$ for all H/D gradually decreased.

Figure 7 shows the changes in the absolute values of $C_{pe,min}$ due to separation and reattachment as the opening ratio increased. When the opening ratio was 0 %, the absolute values were relatively higher than in the other cases due to the direct influence of the vortex via flow separation on the windward wall surface. This difference occurs because in the case of the 10, 30, and 50 % opening ratios, the open space is not directly affected by the vortex. Thus, as the opening ratio increased, it was found that the larger values of $C_{pe,min}$ obtained were less affected by the vortex created by separation due to the larger open space.

Figure 8 shows that for $\alpha = 0.21$, the largest absolute value of $C_{pe,min}$ increased with H/D, with the maximum value occurring at $H/D = 0.5$, whereas for $\alpha = 0.30$, the

![Figure 7. Reattachment position by opening ratio ($\alpha = 0.30$).](image1)

![Figure 8. Comparison of the largest $C_{pe,min}$ at $\alpha = 0.21$ and 0.30 (at an opening ratio of 0 %).](image2)
largest absolute value was obtained at \( H/D = 0.3 \). This difference occurred because the turbulence intensity at \( \alpha = 0.30 \) (22\%) was larger than that at \( \alpha = 0.21 \) (17\%). Thus, as the degree of increase in the turbulence intensity grew considerably with decreasing \( H/D \) due to the complex turbulence arising from the ground surface, the absolute value of \( C_{pe,\text{min}} \) decreased in the \( \alpha = 0.30 \) compared to the \( \alpha = 0.21 \) case.

3.1.2. External positive peak pressure coefficients on roof surface \((C_{pe,\text{max}})\)

Figure 9 shows the \( C_{pe,\text{max}} \) of a dome roof for \( H/D = 0.1 \) and 0.5 and opening ratios of 0–50 % at \( \alpha = 0.30 \). The flow lines with the largest values are illustrated; the \( x \)-axis represents the normalized radius and the \( y \)-axis represents \( C_{pe,\text{max}} \). In this case, the normalized radius 0 of the \( x \)-axis is at the centre of the dome, and 1 is on the windward side. Figure 9(a) shows the largest absolute values for each wind direction on the closed roof. In the case of \( C_{pe,\text{min}} \), the lines with the largest absolute values for each wind direction did not show significant differences, and thus their values occurred at similar positions. However, in the case of \( C_{pe,\text{max}} \), the largest absolute value was obtained at \( L11 \) with a wind direction of 60°, whereas for \( H/D = 0.2 \), it was obtained at \( L11 \) with a wind direction of 80°, for \( H/D = 0.3 \) it was obtained at \( L10 \) with a wind direction of 90°, for \( H/D = 0.4 \) it was obtained at \( L1 \) with a wind direction of 0°, and for \( H/D = 0.5 \) it was obtained at \( L11 \) with a wind direction of 30°. Considering this trend, the absolute value of \( C_{pe,\text{max}} \) is at its largest at locations on the dome parallel to the wind direction on the windward side. In Figure 9(b-d), larger absolute values are shown for the roofs with opening ratios of 10–50 % than for the closed roof. This is because the more complicated turbulence after separation due to the open space of these roofs causes larger absolute values of \( C_{pe,\text{max}} \) to be obtained compared to the roof with an opening ratio of 0 %. For the roofs with opening ratios of 10–50 %, the largest absolute values of \( C_{pe,\text{max}} \) showed similar values and variations without significant differences.

Figure 10 shows the \( C_{pe,\text{max}} \) values for a closed roof with \( \alpha = 0.21 \); the largest absolute value at the edge of the roof was 0.7, which was smaller than 1.3, the largest absolute value for \( \alpha = 0.30 \). This is because the turbulence intensity was higher for \( \alpha = 0.30 \) than for \( \alpha = 0.21 \). Although not shown in the graphs, this trend was the same in the case of the 10, 30, and 50 % opening ratios, and the wind direction and line trends that showed the largest absolute values of \( C_{pe,\text{max}} \) were similar to those in the case of \( \alpha = 0.30 \).

**Figure 9.** Variation of \( C_{pe,\text{max}} \) depending on opening ratio for \( \alpha = 0.30 \): (a) opening ratio of 0 %, (b) 10 %, (c) 30 %, and (d) 50 %.
3.2. Internal negative peak pressure coefficients on outermost interior roof (C_{pi, min})

Figure 11 shows the variation of the internal negative peak pressure coefficient at the outermost interior roof location, C_{pi, min}, according to H/D for a spherical dome roof and the elliptical dome roof under the two evaluated oncoming flow directions. For the elliptical dome roof, the largest absolute values were reported for all wind directions measured at the 12 pressure taps in this study. At the outermost interior point of the roof, negative pressure coefficients dominate, so only C_{pi, min} was analysed. Figure 11(a,b) show the
results of previous research on spherical dome roofs. In general, the variations in the absolute values of $C_{pi, \text{min}}$ with increasing $H/D$ are not significant; hence, only the variations in the absolute values of $C_{pi, \text{min}}$ according to changes in the oncoming flow and opening ratio are shown in Figure 11. Figure 11(c, d) show the $C_{pi, \text{min}}$ obtained in this study for an elliptical dome roof. As the opening ratio increased, the absolute values of $C_{pi, \text{min}}$ tended to increase, and as $H/D$ increased, the absolute values of $C_{pi, \text{min}}$ increased for the case of the 10% opening ratio, whereas they decreased for opening ratios of 30 and 50%; the degree of increase was larger at $\alpha = 0.30$ than at $\alpha = 0.21$. These patterns were due to the same reason as previously described for Figure 6, i.e., the values obtained for the cases with a 30 and 50% opening ratio were likely less affected by the vortex created by separation due to the larger open space. This result can be interpreted to indicate that, apart from the influence of variation in the opening ratio, the elliptical dome roof is more sensitive to changes in the turbulence intensity and the $H/D$ than the spherical dome roof compared to the change in $\alpha$.

Figure 12 shows the absolute values of $C_{pi, \text{min}}$ at the outermost interior roof location for each $H/D$ according to the turbulence intensity change and opening ratios of 10, 30, and 50 % at $\alpha = 0.21$ and 0.30. Figure 12(a) shows the absolute values of $C_{pi, \text{min}}$ with an opening ratio of 10 % for both $\alpha = 0.21$ and 0.30, with the absolute values increasing with increasing $H/D$. Figure 11(b,c) show that the absolute values of $C_{pi, \text{min}}$ decrease with increasing $H/D$ for opening ratios of 30 and 50 %, and as opposed to the case with an opening ratio of 10 %.

### 3.3. External peak pressure coefficients for cladding design

#### 3.3.1. Comparison with Japanese wind load code (AIJ-RLB (2015))

The current external peak pressure values for cladding design in the AU-RLB (2015) code are provided for various values of $f/D = 0$, 0.05, 0.1, 0.2, and 0.5, and of $H/D = 0, 0.25$, and 1. In this study, the wind tunnel test used values of $f/D = 0.1$ and $H/D = 0.1, 0.2, 0.3, 0.4$, and 0.5; for the code comparison, similar values to those in the code, $f/D = 0.1$, and $H/D = 0.2$ and 0.3, were used for the analysis (Table 1). The values for the negative and positive peak pressure coefficients for cladding design according to terrain category were based on the wind tunnel test conducted by Noguchi and Umeda (2003), which correspond to power-law indices $\alpha = 0.15$ and 0.27 with a 1 s moving average time. Because the peak pressure coefficients were larger at $\alpha = 0.30$ than at $\alpha = 0.21$ while the overall variation trends were similar, the data for $\alpha = 0.30$ were used for comparison with the code values.

In the code, a dome roof is divided into three zones as shown in Figure 13, where $R_n$ is the roof edge, $R_0$ is the middle section, and $R_f$ is the section that includes the dome centre. Because the values in the current code are presented only for the case of a closed circular dome roof, the experimental values for an elliptical dome roof with an opening ratio of 0 % were compared with the standard values in the code.

Figure 14 compares the peak pressure coefficients presented by AU-RLB (2015) for $f/D = 0.1$ and $H/D = 0.25$ with the experimental values obtained for $H/D = 0.2$ and 0.3. Figure 13(a) shows that the experimentally obtained negative peak pressure coefficients for both

![Figure 12. Variation of $C_{pi, \text{min}}$ according to turbulence intensity of outermost interior roof location: (a) opening ratio of 10 %, (b) 30 % and (c) 50 %](image-url)
Table 1. Peak pressure coefficients for cladding design prescribed in Japanese wind load code and results.

(a) AIJ-RLB (2015)

| $f/D$ | $a$   | $H/D$ | $R_a$ | $R_b$ | $R_c$ | $R_a$ | $R_b$ | $R_c$ |
|------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.1  | 0.27  | 0.25  | 0.7   | 0.3   | 0.0   | −4.2  | −2.2  | −1.4  |

(b) Experimental value

| $f/D$ | $a$   | $H/D$ | $R_a$ | $R_b$ | $R_c$ | $R_a$ | $R_b$ | $R_c$ |
|------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.1  | 0.30  | 0.2   | 1.2   | 0.5   | 0.2   | −2.7  | −1.6  | −1.7  |
|      | 0.3   | 0.8   | 0.3   | 0.3   | 0.1   | −2.7  | −1.6  | −1.6  |

$H$: wall height
$D$: building diameter
$f$: roof rise

Figure 13. Classification of roof area based on Japanese wind load code (opening ratio of 0%).
3.3.2. Comparison with proposed external peak pressure coefficients for spherical dome with openings

Table 2 shows the proposed values of the negative and positive peak pressure coefficients for cladding design obtained through a wind tunnel test on a retractable spherical dome roof conducted by Kim et al. (2019) in a previous study. For the experimental conditions, opening ratios of 10, 30, and 50 %, f/D = 0.1, and H/D values from 0.1 to 0.5 were used, corresponding to power-law indices α = 0.15 and 0.21 with a 1 s moving average time. The positive and negative peak pressure coefficients of the elliptical retractable dome roof obtained through the experiments conducted in this study were compared with the previously proposed values provided in Table 2. Note that because the absolute values were larger at α = 0.30 than at α = 0.21 and their overall trends of variation were similar, the data for α = 0.30 were used for comparison.

The roof region was divided into two zones for analysis, as shown in Figure 15: Rg covers the area along the roof edge, where relatively large peak pressure coefficients were obtained, and Rn covers the rest of the roof including the dome centre. The boundary delineating the different roof region classifications was based on the normalized radius at which the largest

Figure 14. Comparison of Cpe,min and Cpe,max with Japanese wind load code for opening ratio of 0 %, α = 30: (a) Cpe,min and (b) Cpe,max.

Table 2. Proposed peak pressure coefficients for cladding design for dome with openings (Kim et al. 2019).

| (a) External positive peak pressure coefficients | Zone 1 (d x 0.3) | Zone 2 (d x 0.7) |
|------------------------------------------------|----------------|----------------|
| f/D                                             | H/D           | r/D = 0.1      | r/D = 0.3      | r/D = 0.5      | r/D = 0.1      | r/D = 0.3      | r/D = 0.5      |
| 0.1                                             | 0.1           | 1.2            | 0.9            | 0.8            | 0.2            | 0.2            | 0.1            |
| 0.2                                             | 0.2           | 1.1            | 0.6            | 0.5            | 0.1            | 0.0            | 0.0            |
| 0.3                                             | 0.3           | 0.8            | 0.7            | 0.3            | 0.0            | 0.0            | 0.1            |
| 0.4                                             | 0.4           | 0.6            | 0.3            | 0.3            | 0.0            | 0.1            | 0.0            |
| 0.5                                             | 0.5           | 0.6            | 0.3            | 0.1            | 0.1            | 0.0            | 0.1            |

| (b) External negative peak pressure coefficients |
|------------------------------------------------|
| 0.1                                             |
| 0.1                                             | 0.1           | 1.4            | 1.6            | 1.8            | 1.3            | 1.3            | 1.2            |
| 0.2                                             | 0.2           | 1.7            | 1.9            | 1.8            | 1.3            | 1.3            | 1.2            |
| 0.3                                             | 0.3           | 1.8            | 1.9            | 1.9            | 1.4            | 1.4            | 1.4            |
| 0.4                                             | 0.4           | 1.7            | 1.9            | 1.9            | 1.3            | 1.3            | 1.3            |
| 0.5                                             | 0.5           | 1.9            | 2.0            | 1.8            | 1.4            | 1.4            | 1.4            |

H/D = 0.2 and 0.3 exceeded the standard value in the Rg region. Similarly, Figure 13(b) shows that the experimentally obtained positive peak pressure coefficients for both H/D = 0.2 and 0.3 exceeded the standard code values in all three regions.

r: open area

d: roof diameter

H: wall height

D: building diameter

f: roof rise

H/D = 0.2 and 0.3 exceeded the standard value in the Rg region. Similarly, Figure 13(b) shows that the experimentally obtained positive peak pressure coefficients for both H/D = 0.2 and 0.3 exceeded the standard code values in all three regions.
peak pressure coefficient was observed and the location at which the sharp change in absolute coefficient became gentler. Thus, the 30% of the roof radius nearest from the edge was classified as Zone 1 and the remaining 70% of the roof radius was classified as Zone 2.

Figure 16 shows a comparison of the $C_{pe,min}$ values of the spherical dome roof proposed in previous research for opening ratios of 10%, 30%, and 50% ($H/D = 0.1$ ($C_{pe,max}$), 0.5 ($C_{pe,min}$)) with the experimental values for the elliptical dome roof with $H/D = 0.1, 0.2, 0.3, 0.4$, and 0.5. In Zone 1, the experimentally obtained absolute values of $C_{pe,min}$ were not significantly different from the previously proposed values and exhibited similar trends, but in the case of opening ratios of 10 and 50%, the experimental values exceeded the proposed values from the previous research. In Zone 2, the experimentally obtained absolute values of $C_{pe,min}$
were larger than the proposed values at all opening ratios (Figure 16(a-c)).

In the case of $C_{pe,max}$, the experimental values exceeded the proposed values for all opening ratios in Zone 1 and Zone 2. The graph in Figure 17 shows the $C_{pe,max}$ values for an opening ratio of 10 % as an example.

### 3.3.3. Proposed external peak pressure coefficients for elliptical domes according to opening ratio

The external peak pressure coefficients were proposed for the cladding design of an elliptical dome roof opening from the edge to the centre. As seen previously, for a dome with a closed roof, when compared to the values in the AIJ-RLB (2015) code, the experimental values of $C_{pe,max}$ exceeded the code values in all regions, whereas the experimental values of $C_{pe,min}$ exceeded the code values in region $R_c$, but complied with the code in regions $R_a$ and $R_b$. Because the values at both $\alpha = 0.30$ and $0.21$ exceeded the code values, the experimental values at $\alpha = 0.30$ were applied to generate the proposed coefficients, as they showed larger absolute values better suited to comparison and analysis. For consistency with the current wind

![Figure 17. Comparison of $C_{pe,max}$ for an opening ratio of 10% with proposed values from previous research.](image)

![Figure 18. Classification of roof area of elliptical dome with closed roof.](image)
load code AIJ-RLB (2015), the dome was classified into Zone 1, Zone 2, and Zone 3 as shown in Figure 18.

Figure 19(a) shows the variation in $C_{pe,min}$ according to dome region with an opening ratio of 0%. The proposed values of $C_{pe,min}$ varied from $-2.5$ to $-2.7$ based on the $H/D$ at the end of roof ($D/8$) in Zone 1. In Zone 2, between the centre of dome and end of the roof, the proposed values of $C_{pe,min}$ varied from $-1.4$ to $-1.6$. In Zone 3, the centre of the dome ($D/2$), the proposed values of $C_{pe,min}$ varied from $-1.5$ to $-1.7$. However, because the proposed $C_{pe,min}$ values in Zone 2 were similar to those in Zone 3, it was considered safe to use $-1.7$ for Zone 2 as well. Figure 19(b) shows the variation in $C_{pe,max}$. The proposed values of $C_{pe,max}$

Table 3. Proposed peak pressure coefficients for cladding design for elliptical dome with closed roof.

| $f/D$ | $H/D$ | External positive peak pressure coefficients | External negative peak pressure coefficients |
|-------|-------|---------------------------------------------|---------------------------------------------|
|       |       | $R_a$ | $R_b$ | $R_c$ | $R_a$ | $R_b$ | $R_c$ |
| 0.1   | 0.1   | 1.3   | 0.6   | 0.4   | -2.6  | -1.4  | -1.5  |
| 0.2   | 1.2   | 0.5   | 0.2   | -2.7  | -1.6  | -1.7  |
| 0.3   | 0.8   | 0.3   | 0.1   | -2.7  | -1.6  | -1.6  |
| 0.4   | 0.6   | 0.2   | 0.0   | -2.5  | -1.5  | -1.5  |
| 0.5   | 0.4   | 0.1   | 0.0   | -2.5  | -1.5  | -1.5  |

$H$: wall height
$D$: building diameter
$f$: roof rise

Figure 19. Proposed $C_{pe,min}$ and $C_{pe,max}$ and corresponding zoning with closed roof: (a) $C_{pe,min}$ and (b) $C_{pe,min}$.

Figure 20. Classification of roof area of elliptical dome with opening.
vary from 0.4 to 1.3 in Zone 1, from 0.1 to 0.6 in Zone 2, and from 0.0 to 0.4 in Zone 3. The proposed peak pressure coefficients for each $H/D$ with an opening ratio of 0% are listed in Table 3.

As for the classification of retractable roof regions, based on the variation of the negative and positive peak pressures, the absolute values in the dome centre become similar at a normalized radius of 0.7. Thus, Zone 1 is defined from the end of roof to 30% (15% of both ends in case of the diameter) of the roof radius and Zone 2 is defined as the remaining 70% of the roof radius, including the dome centre (Figure 20),
which is similar to the regions proposed in Kim et al. (2019).

Figure 21 shows the variation in $C_{pe,min}$ according to the proposed retractable roof region definitions. The proposed values of $C_{pe,min}$ vary from $-1.7$ to $-2.2$ according to the $H/D$ at the end of roof (normalized radius $r^*$ of 1) corresponding to Zone 1, and from $-1.4$ to $-1.7$ in the centre of the dome (normalized radius $r^*$ of 0) corresponding to Zone 2. Figure 22 similarly shows the variation in $C_{pe,max}$. The proposed values of $C_{pe,max}$ vary from 0.5 to 1.6 in Zone 1 and 0.0 to 0.6 in Zone 2. The proposed peak pressure coefficients for each $H/D$ for the retractable roof are listed in Table 4.

4. Concluding remarks

This study investigated the wind pressure characteristics of an elliptical plan retractable dome roof. Because there are no current codes for determining the external peak pressure for the cladding design of an elliptical dome roof, this study was conducted to propose new code values for this case. Wind tunnel experiments were therefore performed on a series of retractable elliptical dome roofs with varying wall height-to-span ratios (0.1, 0.5) and opening ratios (0, 10, 30, and 50 %). The characteristics of the resulting peak pressure coefficients were analysed with a focus on comparing the current code values with the proposed values. The case of a roof with an opening ratio of 0 % was accordingly compared with the values in the Japanese wind load code (AU-RLB, 2015). The experimentally obtained elliptical retractable dome roof pressure coefficients were also compared with the peak pressure coefficients for the cladding design of a spherical retractable dome roof proposed in a previous study. The negative and positive peak pressure coefficients in the closed and open states of the elliptical dome roof were then proposed based on the experimental results. The key findings can be summarised as follows.

1) For $a = 0.21$, the absolute values of $C_{pe,max}$ decreased with increasing $H/D$, whereas the absolute values of $C_{pe,min}$ increased with increasing $H/D$. In other words, the largest absolute values were obtained at $H/D = 0.1$ for $C_{pe,max}$ and $H/D = 0.5$ for $C_{pe,min}$. For $a = 0.30$, the largest absolute value of $C_{pe,max}$ was shown at $H/D = 0.1$, indicating a similar trend to that for $a = 0.21$, while the largest absolute value of $C_{pe,max}$ was obtained at $H/D = 0.3$. This phenomenon is thought to arise from the occurrence of relatively high turbulence intensity according to the changes in $a$.

2) The absolute values of $C_{pe,min}$ at the outermost interior of the roof increased with opening ratio and were similar for both values of $a$. As the opening ratio increased, the absolute value of $C_{pe,min}$ increased. At an opening ratio of 10 %, the absolute value of $C_{pe,min}$ increased with increasing $H/D$, whereas it gradually decreased with increasing $H/D$ at opening ratios of 30 % and 50 %. Furthermore, the degree of increase in

| $r/D$ | $H/D$ | $r/D$ | $H/D$ | $r/D$ | $H/D$ |
|-------|-------|-------|-------|-------|-------|
|       |       |       |       |       |       |
| 0.1   | 0.1   | 1.6   | 0.3   | 1.5   | 0.5   |
| 0.2   | 1.3   | 1.2   | 0.3   | 0.8   | 0.5   |
| 0.3   | 0.8   | 1.2   | 0.3   | 0.6   | 0.5   |
| 0.4   | 0.6   | 1.2   | 0.3   | 0.6   | 0.5   |
| 0.5   | 0.6   | 1.2   | 0.3   | 0.6   | 0.5   |

(b) External negative peak pressure coefficients

| $r/D$ | $H/D$ | $r/D$ | $H/D$ | $r/D$ | $H/D$ |
|-------|-------|-------|-------|-------|-------|
| 0.1   | 0.1   | -1.7  | 0.3   | -2.0  | 0.5   |
| 0.2   | 0.1   | -1.8  | 0.3   | -2.0  | 0.5   |
| 0.3   | 0.1   | -2.0  | 0.3   | -2.0  | 0.5   |
| 0.4   | 0.1   | -1.9  | 0.3   | -2.0  | 0.5   |
| 0.5   | 0.1   | -1.9  | 0.3   | -2.0  | 0.5   |

Table 4. Proposed peak pressure coefficients for cladding design of elliptical dome with openings. (a) External positive peak pressure coefficients.
absolute value of $C_{pe,min}$ with $H/D$ was larger at $\alpha = 0.30$. This finding is different from previous research conducted on a spherical dome roof (Kim et al. 2019). Thus, this study demonstrates that an elliptical dome roof is relatively more sensitive to change in $H/D$ and $\alpha$ than a spherical dome roof.

3) The $C_{pe,min}$ and $C_{pe,max}$ values for the elliptical dome roof in the closed state were compared with the values provided by the AJI-RLB (2015) code. The results indicated that the experimental values for $C_{pe,min}$ exceeded the code values for all $H/D$ only in region $R_p$, which is the centre portion of the dome. For the other regions, the experimental values complied with the code values and showed the likelihood of a conservative design. However, the experimental values of $C_{pe,max}$ exceeded the code values in all three regions ($R_p$, $R_b$, and $R_c$) for all $H/D$ values and were, thus, unsuitable to use with the specification. Therefore, the negative and positive peak pressure coefficients for a 0% opening ratio were proposed as the basis for the cladding design of an elliptical retractable dome roof. The proposed values of the negative peak pressure coefficients ranged according to $H/D$ from $-2.5$ to $-2.7$ in Zone 1, $-1.4$ to $-1.6$ in Zone 2, and $-1.5$ to $-1.7$ in Zone 3. The proposed values for the positive peak pressure coefficients ranged according to $H/D$ from 0.4 to 1.3 in Zone 1, 0.1 to 0.6 in Zone 2, and 0.0 to 0.4 in Zone 3.

4) A comparison of the $C_{pe,min}$ and $C_{pe,max}$ values for the elliptical dome roof under varying degrees of opening with the negative and positive peak pressure coefficients proposed in previous research indicated that, in the case of $C_{pe,min}$, the experimental values exceeded the proposed values for all $H/D$ in Zone 2, which is the centre of the dome area. In Zone 1, along the edge of the dome, the experimental values exceeded the proposed values, though the two sets of values were similar. In the case of $C_{pe,max}$, the experimental values exceeded the proposed values in all cases. Therefore, the values of the negative and positive peak pressure coefficients for the cladding design of elliptical retractable dome roof were proposed based on the experimental values. The proposed values for the negative peak pressure coefficients ranged according to degree of opening from $-1.7$ to $-2.2$ in Zone 1 and from $-1.4$ to $-1.7$ in Zone 2. The proposed values for the positive peak pressure coefficients range according to degree of opening from 0.5 to 1.6 in Zone 1 and 0.0 to 0.6 in Zone 2.

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No potential conflict of interest was reported by the author(s).

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