International Journal of High-Rise Buildings
December 2019, Vol 8, No 4, 283-290
https://doi.org/10.21022/IJHRB.2019.8.4.283

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Characteristics of Negative Peak Wind Pressure acting on Tall Buildings with Step on Wall Surface

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Abstract

Corner cut, corner chamfered or a building shape change are adopted in the design of tall buildings to achieve aerodynamic superiority as well as response reduction. Kikuchi et.al pointed out that large negative peak external pressures can appear near the inside corner of set-back low rise buildings. It is therefore necessary to pay attention to facade design around steps in building surfaces. Peak wind pressures for corner cut or corner chamfered configurations are given in the AIJ code. However, they cannot be applied where there are many variations of vertical and horizontal steps. There has been no previous systematic research on peak wind pressures around steps in building surfaces. In this study, detailed phenomenon of peak wind pressures around steps in buildings are investigated focusing on vertical and horizontal distances from the building's corner.

Keywords: External peak wind pressure, Wind tunnel experiment, Tall building with step

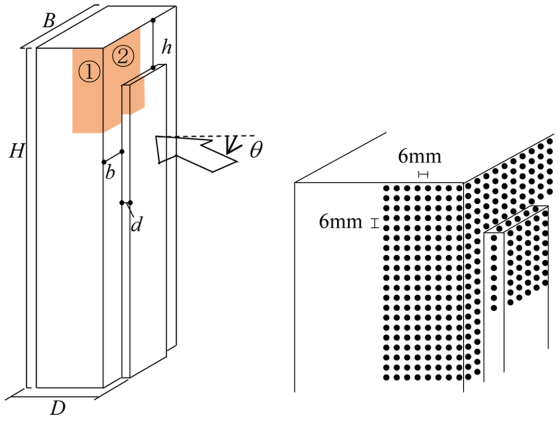
1. Introduction

Nowadays, the corners of buildings are chamfered, or cut off in many cases, to improve their aerodynamics. Tanaka et al. (2013) and Bandi et al.(2013) indicated that it is possible to increase the aerodynamic advantages of buildings by modifying the shapes of their corners or altering them vertically. However, Kikuchi et al. (2010) pointed out that buildings with setbacks force air flow to contract around the recessed areas, which augments the absolute value of peak external pressure locally. Since the peak external pressures acting on the horizontally and vertically chamfered edges of buildings are different from those on buildings with un-chamfered corners, it is necessary to pay careful attention to this fact in design. AIJ-RLB (2015) gives peak external pressure coefficients for relatively simple chamfered or cut corners, but these cannot be applied to complex steps in walls. In addition, there has been no systematic research on steps in building walls and their peak external pressure coefficients, so it is difficult to accurately estimate the wind loads on their exteriors. In this study, the authors vary the horizontal and vertical distances between steps in walls for two building shapes, and research the trend of peak external pressure coefficients, focusing on the areas affected by the steps. In this paper, vertical and horizontal chamfered corners are all called "steps."
and horizontal distance b. For the one with a side ratio of

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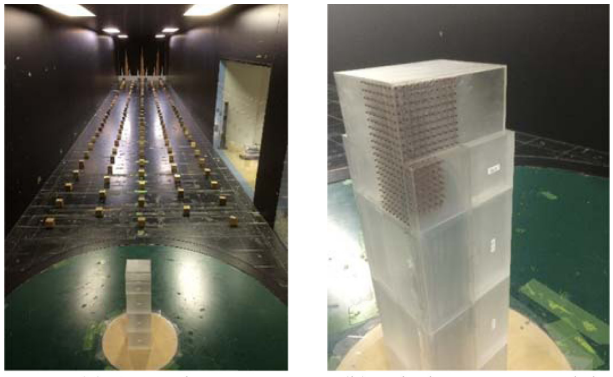
2. Outline of experiment and analysis methods

The step-mounted building model shown in Figure 1 and Photo 1 was used for the wind tunnel experiment. The scale of the model was 1/350, and as shown in Figure 1(b), wind pressure measurement points were concentrated around the corners of the top of the model (represented by the shaded area in Figure 1(a)), and wind pressures were measured simultaneously at a total of 357 points. Table 1 shows the dimensions of the experimental model. Two planar shapes were adopted. The ratios of width to depth (side ratio) were 1 and 2. For the one with a side ratio of 1, there were 29 combinations of vertical distance *h*



(a) Experimental model (b) Location of pressure taps

Figure 1. Outline of experimental model.



(a) Over view (b) Wind pressure model

Photo 1. Setup of wind pressure model.

Table 1. Dimensions of experimental models

Model scale = 1/350	Side ratio	
	$B/D = 1$	$B/D = 2$
Height H	480 mm (168 m)	
Depth D	120 mm (42 m)	
Width B	120 mm (42 m)	240 mm (84 m)
Step thickness d	12 mm (4.2 m)	
Horizontal distance b	0~30 mm @6 mm	0~24 mm @6 mm
Vertical distance h	0~60 mm @6 mm	

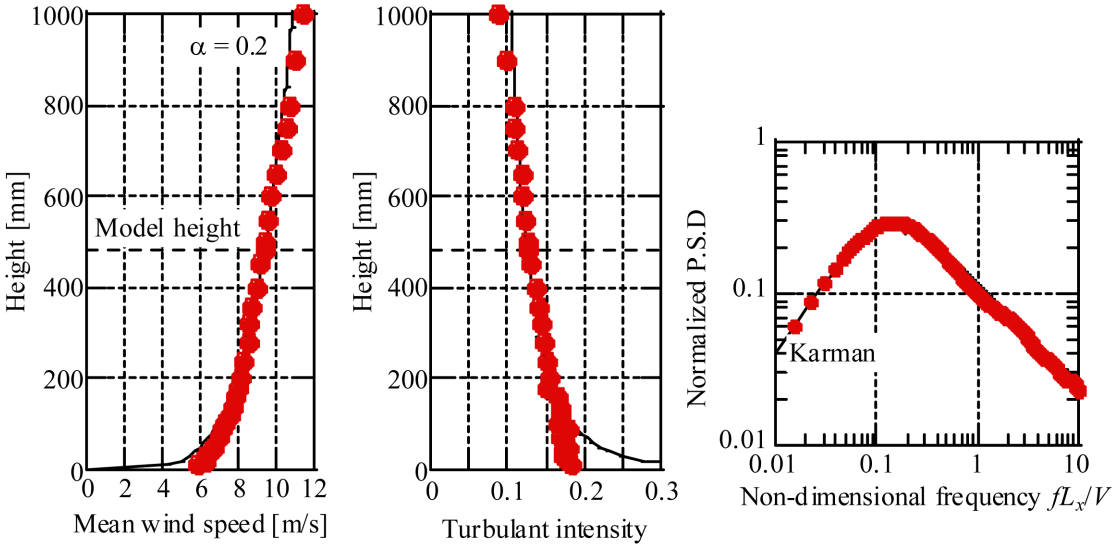
() in full scale

2, there were 39 combinations of vertical distance h and horizontal distance b. Here, h represents vertical distance between the top of the building and the top of the step, while b denotes horizontal distance between the corner of the building and the step. For the experimental air flow, the power law index of the vertical profile α was set at 0.2 (corresponding to terrain roughness category III in AIJ-RLB) as shown in Figure 2.The experimental wind direction was altered at intervals of 5° from 0° to 180° to focus on the negative peak pressure, and measurement was conducted for 37 wind directions. When the basic wind speed was set at 36 m/s assuming the urban center of Tokyo, design wind speed in a 100-year simulation period was approximately 50 m/s. The wind speed scale was 1/5, while the time scale was 1/70. Sampling frequency was 800 Hz, and measurement duration was 10 minutes in actual time for one sample. The effect of tube was corrected with the transfer function. The variations in wind pressure were measured for 10 samples. The negative peak external pressure coefficient (minimum C_p) is defined by Equation (1). Assuming the comparison between AIJ-RLB and the results of the experiment, the moving-average method was used for a period equivalent to 1.0 seconds in actual time (Ohtake (2000)), the ensemble average of the minimum C_ps of 10 samples was obtained, and peak values were evaluated. When the moving average was 0.2 seconds, the absolute value of the minimum C_p became about 20% larger.

3. Distribution of negative peak external pressure coefficients

3.1 Effect of corner cut of building in horizontal plane

Figure 3 shows the distributions of negative peak external pressure coefficients for vertical distance $h = 0$ and various horizontal distances b, focusing on the case where wind direction $\theta = 15°$, which had the minimum C_p on the step-free side (1) of the rectangular prism with a side ratio of 1. When horizontal distance $b = d$ as shown in Figure 3(b), negative peak external pressure coefficients emerged homogeneously in the vertical direction on the lateral side of the step (circled by the dashed line), and there was a two-dimensional distribution in the vertical direction on



(a) Mean wind speed (b) Turbulence intensity (c) PSD of fluctuating wind speed U_H

Figure 2. Wind speed profile and power spectrum density function of fluctuating wind speed.

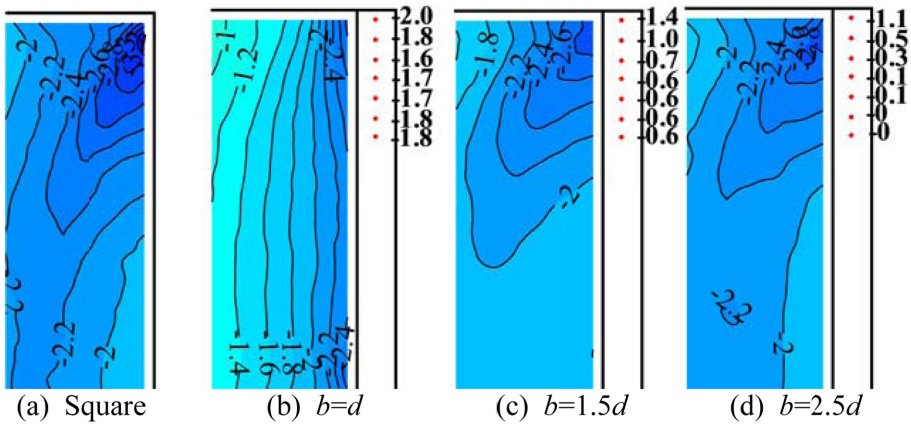


Figure 3. Negative peak external pressure distributions with different horizontal distances. (*B/D*=1, Surface ①, Wind direction $\theta = 15^{o}$, Vertical distance $h = 0$)

the lateral side of the building. As shown in Figures 3 (c) and (d), when horizontal distance $b = 1.5$d or over, a three-dimensional vortex was generated on the lateral side of the building like the case of the rectangular prism with a side ratio of 1.

Figure 4 focuses on the side (2) with $\theta = 75^{o}$ axially opposite to Figure 3 with respect to wind direction 45°. Figure 4 (b), in which horizontal distance $b =$ d, shows vertically homogeneous negative peak external pressure coefficients around the recessed part of the building. Around the top of the step, circled by the solid line, the area of the wind pressure measurement points is so small that a negative peak external pressure coefficient with a large absolute value apparently emerged locally, but this is considered to be the same as that shown in Figure 3 (b). As shown in Figures 4 (c) and (d), the recessed part and step of the building have two-dimensional distributions in the vertical direction. It can be understood that a step makes it difficult to generate a three-dimensional vortex.

3.2 Effect of corner cut in vertical plane

Figure5 shows the distributions of negative peak external pressure coefficients for horizontal distance $b = 0$ and various vertical distances h, focusing on the case of wind direction $\theta = 15°$, which had the minimum C_p on the step-free side (1) of a rectangular prism with a side ratio of 1. From now on, vertical distance h and horizontal distance b will be made dimensionless with step thickness d. On the rectangular prism with a side ratio of 1 (Figure5 (a)), there is a negative peak external pressure coefficient with the largest absolute value around the top of the building (circled by the solid line). The minimum C_p emerged in the area circled by the solid line below the top of the step when vertical distance $h = 1.5\ d$ (Figure5 (b)). For vertical distances $h =$ 2d and 5d (Figures 5 (c) and (d)), the location of the minimum C_p circled by the solid line varied with vertical distance h. The local negative peak external pressure coefficient, which emerged at the step, was continuous from the lateral side of the step to the building side, and is considered due to the vortex originating from the corner of the step. When we focus on the areas circled by the dashed lines in Figures 5 (b) to (d), it can be understood that a relatively large negative peak external pressure coefficient emerges and varies according to vertical distance

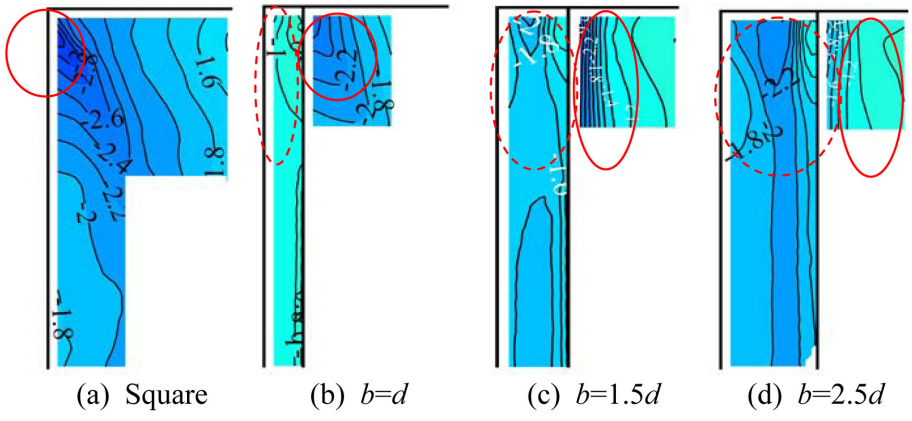
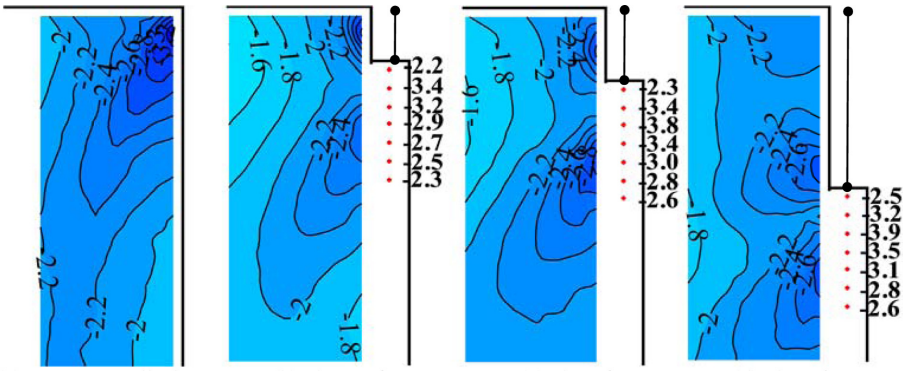


Figure 4. Negative peak external pressure distributions with different horizontal distance. ($B/D = 1$, Surface ②, Wind direction $\theta = 75°$, Vertical distance $h = 0$)



(a) Square cylinder (b) h=1.5d (c) h=2d (d) h=5d

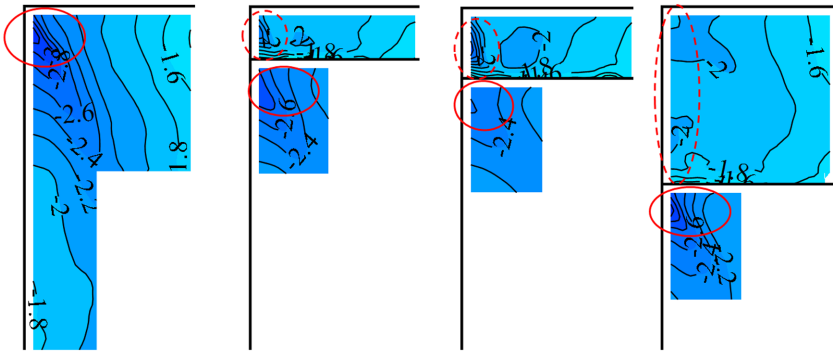
Figure 5. Negative peak external pressure distributions for various vertical distances. (B/D = 1, Surface ①, Wind direction θ = 15°, Horizontal distance b = 0)

h as in the above mentioned case, and this phenomenon can be considered to be the same as the peak external pressure coefficient emerging locally at the upper part of the corner of the step when a step exists on a low-rise building, as indicated in the study of Kikuchi et al (2010).

Figure 6 shows the distributions of negative peak external pressure coefficients for horizontal distance b = 0 and various vertical distances h, focusing on the case of wind direction θ = 75°, which had the minimum C_p on the step-free side (2) of a rectangular prism with a side ratio of 1. On the rectangular prism with the side ratio equal to 1 in Figure 6 (a), a three-dimensional vortex was generated obliquely downward from the top of the building (Okuda et al. (1993)), and a negative peak external pressure coefficient with a large absolute value emerged. The distributions of negative peak external pressure coefficients circled by the solid lines around the top of the step shown in Figures 6 (b) to (d) show the same tendency as (a). This is considered to be due to the three-dimensional vortex, although it is weak. Also in the area between the top of the building and the step circled by the dashed line, a negative peak external pressure coefficient with a relatively large absolute value emerged, but a vortex like that on the rectangular prism of (a) was not generated. This is considered to be due to the separation from the lateral side.

3.3 Effect of combination of corner cut in horizontal and vertical plane

Figure 7 shows an example of a negative peak external pressure coefficient distribution for various vertical distances h, focusing on surface ① of side ratio B/D = 2 for wind direction θ = 15° where the negative peak external pressure coefficient for all wind directions occurred. Figure 7 focuses on the case where horizontal distance b = 1.5d, at which the influence of vertical distance h was the most significant. When vertical distance h = 0.5d, the absolute value of minimum C_p at the top of the step is as large as 1.5, and as vertical distance increases, the absolute value gets closer to 1. The minimum C_p at the top of the building circled by the solid line is −2.6, indicating the minimum absolute value, when h = 0.5d, and gets closer to −3.6 when vertical distance is 2d or over, that is, it becomes more similar to the case of a rectangular prism with a side ratio of 2. Since the horizontal distance is 1.5d, a local negative peak external pressure coefficient, which emerges around the recessed part of the step as shown in Figure 7, did not



(a) Square (b) h=1.5d (c) h=2d (d) h=5d

Figure 6. Negative peak external pressure distributions for various vertical distances (B/D = 1, Surface ②, Wind direction θ = 15°, Horizontal distance b = 0)

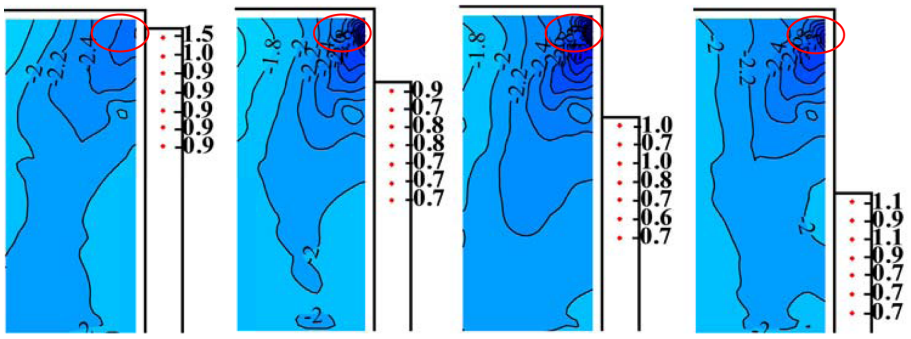


Figure 7. Negative peak external pressure distributions for different vertical distances ($B/D = 2$, Surface ①, Wind direction $\theta = 15^{o}$, Horizontal distance $b = 1.5$d)

emerge.

Figure 8 shows the distributions of negative peak external pressure coefficients on Surface① for various horizontal distances b, focusing on the case where vertical distance h = 3d, at which the influence of horizontal distance b is significant. The wind direction θ at which a negative peak external pressure coefficient with the largest absolute value emerged on the side (1) was 10° in Figure 8 (a), 0° in Figure 8 (b), and 15° in Figures 8 (c) and (d). When horizontal distances $b = 0.5$d and d, the absolute value of the minimum C_p at the step is large, and it emerges on the lateral side of the building around the top of the step circled by the solid line. When horizontal distances $b = 1.5$d and 2d, the absolute value of the minimum C_p at the step is small, and the minimum C_p emerges due to the three-dimensional vortex around the top of the building. The formation of a three-dimensional vortex on a building is closely related to the horizontal and vertical distances of a step.

4. Negative peak external pressure coefficient in each region

In this section, the minimum C_p of each categorized region with a large absolute value are discussed. Based on the results, the minimum C_p with the largest absolute value for the experimental wind direction in each region as shown in Figure 9 and every measurement point is summarized. Figure 10 shows the variation in region A with a side ratio of 2. It also shows the minimum C_p obtained through the experiment on a rectangular prism with the same side ratio. When horizontal distances $b = 0.5d$ and d, the absolute value is smaller than that of a rectangular prism regardless of vertical distance h. When horizontal distance $b = 1.5d$ and $2d$, the absolute value exceeds that of a rectangular prism, as vertical distance h is $2d$ or over.

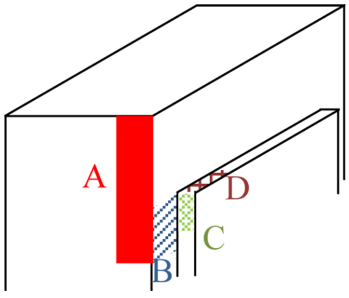


Figure 9. Categorized into 4 regions for minimum external pressure coefficient

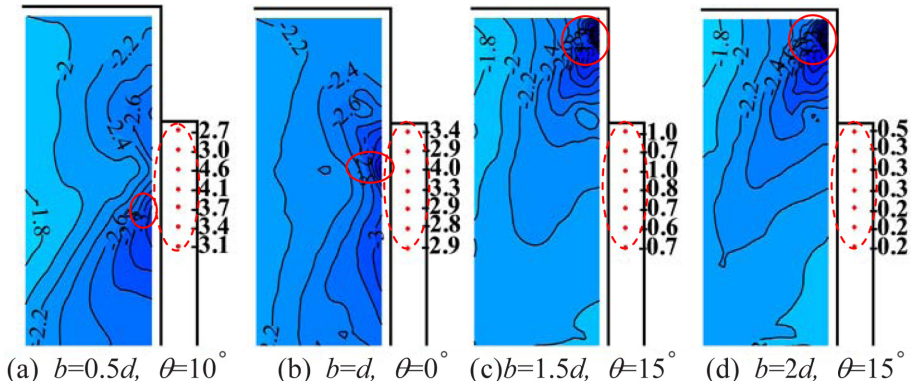


Figure 8. Negative peak external pressure distributions for various horizontal distances ($B/D = 2$, Surface ①, Vertical distance $h = 1.5d$)

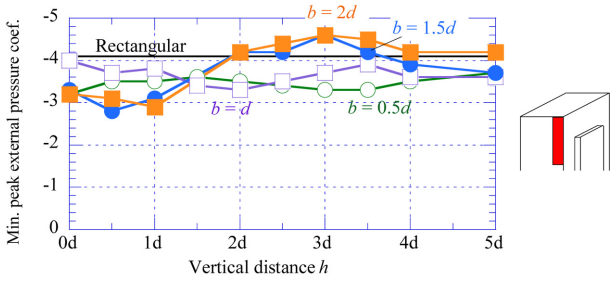


Figure 10. Variations of minimum external pressure coefficient for all wind directions with various step locations. ($B/D = 2$, Region A)

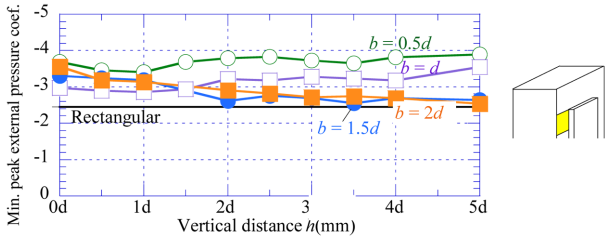


Figure 11. Variations of minimum external pressure coefficient for all wind directions with various step locations. (B/D=2, Region B)

When horizontal distance $b = 2d$ and vertical distance $h = 3d$, there may emerge a negative pressure (−4.2) that has the largest absolute value. Figure 10 shows the variation in region B with a side ratio of 2. When horizontal distances $b = 0.5d$ and d, the absolute value increases as vertical distance h increases. When horizontal distance $b = 1.5d$ and $2d$, the absolute value decreases. In all cases, the absolute value of the minimum C_p is larger than that of a rectangular prism. In region B with a side ratio of 2, the minimum C_p increases due to the existence of a step, compared with that with a side ratio of 1. Figure 11 shows the variations in wind directions at the measurement points where the minimum C_p with the largest absolute value emerged in region B with a side ratio of 2. When horizontal distance b is short, the minimum C_p with a large absolute value emerges when wind direction angle θ is around 10°, and when horizontal distance b is long, the coefficient emerges when θ is around 90°. When horizontal distance $b = 0.5d$, the absolute value does not vary significantly with vertical distance h. However, when horizontal distance $b = 2d$, the absolute value of the minimum C_p increases as vertical distance h decreases. Thus, the factor in the emergence of the minimum C_p with the largest absolute value in region B is the negative pressure around the recessed part of the step when horizontal distance b is short, and separation from upstream occurs when horizontal distance b is long. Figure 12 shows the variation in region C with a side ratio of 2. When horizontal distances $b = 0.5d$ and d, the absolute value of the minimum C_p increases as vertical distance h increases. When horizontal distances $b = 1.5d$ and $2d$, the absolute value

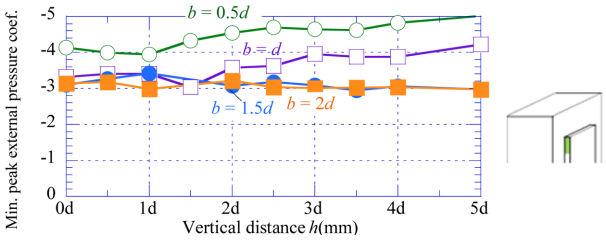


Figure 12. Variations of minimum external pressure coefficient for all wind directions with various step locations ($B/D = 2$, Region C)

does not vary significantly with vertical distance h. For region C, the absolute value of the minimum C_p increases as horizontal distance b decreases, no matter whether the side ratio is 1 or 2.

Figure 13 shows changes of the minimum C_p having the largest absolute value in region B for the side ratio of 2 with wind direction. When horizontal distance b is small, the minimum C_p having a large absolute value occurred near wind direction $\theta = 10°$, and when horizontal distance b was large, it occurred near wind direction $\theta = 90°$. Focusing on horizontal distance b, when $b = 0.5d$, the effect of vertical distance h is small. However, when horizontal distance $b = 2d$, the absolute value of the minimum C_p increases as vertical distance h decreases. It can be understood that the minimum C_p in region B is due to negative pressure generated near the stepped corner when horizontal distance b is small, and when horizontal distance b is large, the minimum C_p is generated due to the separations from the corner. Figure 14 shows the variation in minimum

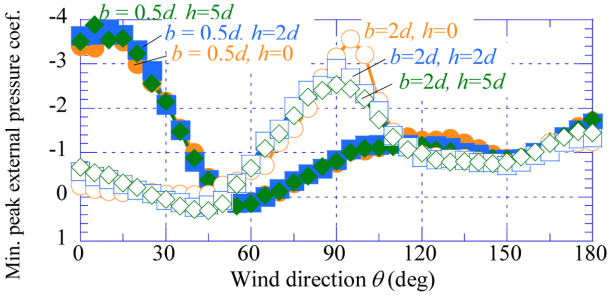


Figure 13. Variations of negative peak external pressure in region B for different wind directions. ($B/D = 2$, Region B)

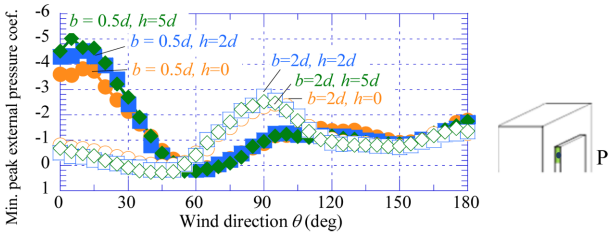


Figure 14. Variations of negative peak external pressure at Point P in region C for different wind directions. ($B/D = 2$, Region C)

C_p at measurement point P, where the absolute value is the largest in region C, with respect to wind direction. When horizontal distance $b = 0.5$d, the absolute value of the minimum C_p is largest when wind direction θ is around 10°. This indicates that the absolute value of the minimum C_p increases as vertical distance h increases. When horizontal distance $b = 2d$, the absolute value of the minimum C_p is largest when wind direction θ is around 90°, and the minimum C_p does not vary significantly with vertical distance h. The variation in the minimum C_p with respect to wind direction at measurement point P is similar to that in region B. The minimum C_p in region C is considered to be due to the vortex around the recessed part of the step when horizontal distance b is short, and due to the separation from the lateral side when b is long.

5. Proposal for a peak external pressure coefficient for cladding design

According to the current wind load code, standards and guidelines, a building with rectangular prism shape, simple corner cuts, or the like is divided into several areas, and a peak external pressure coefficient is given to each region. In this study, the authors propose a step-caused magnification factor γ with respect to the peak wind force coefficient in AIJ-RLB (2015) shown in Equation (2), in order to calculate the wind loads on claddings of buildings with steps.

$$W_C = q_H \gamma \hat{C}_C A_C \tag{2}$$

W_C : Wind load on claddings (N)
$\hat{C}_C$: Peak wind force coefficient of a rectangular prism
A_C : Load-bearing area of claddings
γ : Step-caused magnification factor

$$\gamma = \frac{\text{Negative peak external pressure cofficient due to steps}}{\text{Negative peak external pressure coefficient at a rectangular prism}} \tag{3}$$

Figure 15 shows the magnification factor for cladding design in Region A with side ratio $B/D = 2$. Table 2 shows

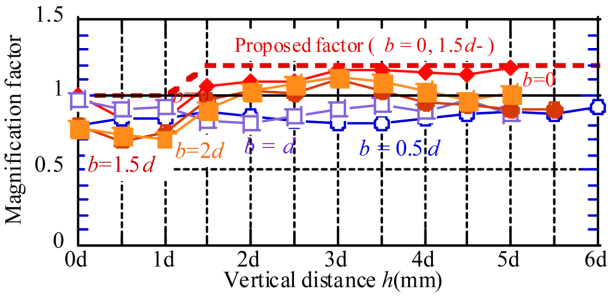


Figure 15. Magnification factor for cladding design. (Region A, Side ratio 2)

Table 2. Magnification factor for cladding design (Region A, Side ratio 2)

		Vertical distance	
		$h/d = 0 \sim 1$	$h/d = 1.5 \sim 6$
Horizontal distance	$b/d = 0$, 1.5~	1.0	1.2
	$b/d = 0.5 \sim 1$	1.0	

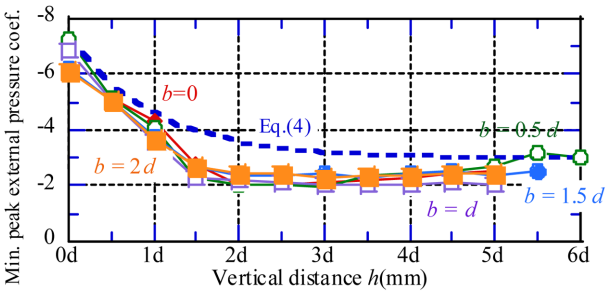


Figure 16. Negative peak external pressure coefficient. (Region D, Side ratio 2)

the magnification factor for design in Region A. Until vertical distance h reaches d, it is possible to use the value for a rectangular prism, but if h exceeds d, a magnification factor γ 20% larger than that for rectangular prism is proposed. When horizontal distance $b = 0.5d$ or d, it is possible to use the value for a rectangular prism ($\gamma = 1$) regardless of vertical distance h.

Figure 16 shows the negative peak external pressure coefficient for cladding design in Region D with side ratio $B/D = 2$. In this region, comparison with a rectangular prism is impossible, so the negative peak external pressure coefficient rather than the magnification factor is proposed as Equation (4). Regardless of horizontal distance b, it is obvious that the absolute value of the negative peak external pressure coefficient decreases when vertical distance h increases.

$$\check{C}_p = (-2.2Se^{(-\sqrt{2}h^*/\sqrt{S})}) - 3 \tag{4}$$

Side ratio: $S = B/D$
Vertical distance: $h^* = h/d$

6. Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP16H04457 and the joint research project of the Wind Engineering Joint Usage/Research Center, Tokyo Polytechnic University.

7. Conclusions

The minimum C_p of a building that has a step in the horizontal and vertical directions with a side ratio of 1 or 2 were examined. The wall surface was classified into a number of regions according to the characteristics of the wind pressure distribution of the minimum C_p, and the

authors summarized the minimum C_p that varies according to the horizontal and vertical distances of the step. There was no significant variation in the wind pressure distribution due to the step when side ratio was 1 or 2. It was found that a three-dimensional vortex is generated at a building according to the location of a step, and the authors were able to identify the wind directions at which the absolute value of the minimum C_p is a local maximum. The authors clarified the region where the minimum C_p with a large absolute value emerges due to a step, compared with the case of a step-less rectangular prism. There are an enormous number of combinations of the position of a step, and this study cannot be said to be sufficient. The authors will keep studying the combinations of building shapes and steps, and discuss the phenomenon of vortex formation through experiments, such as PIV.

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