A STUDY FOR THE WIND FORCE COEFFICIENT OF A TRANSMISSION TOWER FRAME USING WIND TUNNEL

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Abstract: The wind load as a design factor of transmission tower is determined by wind force coefficient of the rectangular frame. This wind force coefficient is changed by several factors such as the section shape of tower frame, solidity ratio, tower body facade and wind direction angle. However, in Korea, the wind response of transmission tower has been partially studied and an experimental study on the estimated of wind force coefficient of a transmission tower rectangular frame has not been conducted. In this study, the characteristics of wind force coefficient of a transmission tower rectangular frame were estimated using a model and tunnel test in some conditions such as various solidity ratios and wind direction angles. For these conditions, several models with different solidity ratios were developed by two methods such as adding frames or increasing frames of 2D and 3D basic models. And the wind direction angle was changed from 0 to 90 degree in 2D model, from 0 to 45 degree in 3D model. From the results, it can be concluded that the wind force coefficient of a transmission tower frame can be used as preliminary data in deciding on the transmission tower's wind load.

1 INTRODUCTION

Most transmission tower frames that were constructed with diverse shapes are rectangular-frame-based solid truss structures. Recently, rectangular-frame-based solid truss structures are being applied to various structures and to transmission towers. The wind force characteristics of the solid-truss-shaped rectangular frame change in a very complex manner according to the section shape, solidity ratio, tower body façade, and wind direction angle (Pagon, 1958). The wind force coefficient of the rectangular frame is a factor for determining the wind load for transmission tower design, which is defined in the KEPCO Design Standard 2008 (DS-1111) and in the Korea Building Code (Korea Electric Power Corporation, 2008 and Architectural Institute of Korea, 2009). In Korea, studies on the wind response of transmission towers have been partially conducted (Min et al., 2006 and Jo et al., 2003), but few experimental studies that estimated the wind force coefficient of rectangular frames.

The wind force coefficient of an angle steel rectangular frame mainly changes according to the solidity ratio, and is almost constant regardless of the Reynolds number. The wind force coefficient of a steel pipe rectangular frame changes according to the Reynolds number of each member of the frame and to the solidity ratio.

In the rectangular tower frame test, the solidity ratio was changed to make a model by adding the tower members to 2D and 3D structures and by increasing the member size. The wind direction angle was changed during the wind tunnel test from 0° to 90° for 2D structures, and from 0° to 45° for 3D structures, and the results were summarized. The tests of the rectangular tower frame were limited to the angle steel members, which are not influenced by the Reynolds number.

2 WIND TUNNEL TEST

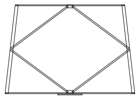
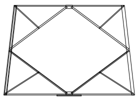
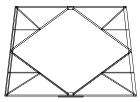
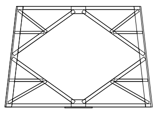
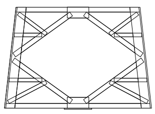
To examine the characteristics of the wind force coefficient of the tower members, 2D and 3D rectangular tower frame models were manufactured for conducting the wind force coefficient estimation test in the 3D wind tunnel.

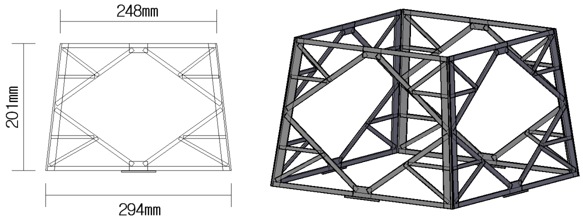
2.1 Rectangular tower frame model for wind tunnel test

Based on the actual angle steel tower, a span was selected for the rectangular tower frame model, and the model size was reduced to 1/30. The basic model size was 29.4 cm for the lower base, 24.8 cm for the upper base, and 20.1 cm tall, and the model was manufactured in 2D and 3D types. The 2D-type models were made into three types by changing the solidity ratio with the addition of members (Types Ⅰ, Ⅱ, and Ⅲ).

Five types of the 3D-type models were made: three types by changing the solidity ratio through the addition of members, as with the 2D type (Types Ⅰ, Ⅲ and Ⅲ), and another two types by increasing the member size (Types Ⅳ and Ⅴ).

Table 1: Rectangular tower frame model shapes

Type (Solidity ratio)	Features	Façade
Type Ⅰ (0.117)	Basic type	
Type Ⅱ (0.130)	One member added to the basic type	
Type Ⅲ (0.140)	Two members added to the basic type	
Type Ⅳ (0.267)	Type Ⅲ member size doubled	
Type Ⅴ (0.378)	Type Ⅲ member size tripled	



(a) 2D shape (b) 3D shape

Figure 1: 3D rectangular frame shape: Type IV

The models were made of balsa. Table 1 and Fig. 1 show the shapes of the test models.

2.2 Wind tunnel airflow and data measurement

The wind tunnel test for the rectangular tower frame was conducted in the large-scale boundary layer wind tunnel in the Hyundai E&C R&D Center. The measurement area in the wind tunnel test room was 25 m long, and its sectional area was 4.5 m wide and 2.5 m high. The spire and roughness block were not used in the wind tunnel for the test at a constant wind velocity. The airflow characteristic was similar to the earth surface roughness D, as shown in Fig. 2. Without the spire and roughness block, the bottom of the model was separated from the ground by 20 cm to remove the wind tunnel boundary layer.

The wind velocity in the wind tunnel was 5.0 m/s at the height of 40 cm. It was measured using a hot wire anemometer, and the measurements were corrected based on the values of the pivot tube. The wind velocity data were measured for 60 s by sampling them at 200 Hz. With the front of the rectangular tower frame as the zero-degree wind direction angle, 11 test wind directions were set at 10° intervals from 0° to 90° (including 45°) in the 2D =- type structure, and 10 wind directions were set at 10° intervals from 0° to 45° in the 3D-type structure. Fig. 3 shows the wind tunnel test for the 2D and 3D rectangular tower frames in the large-scale wind tunnel.

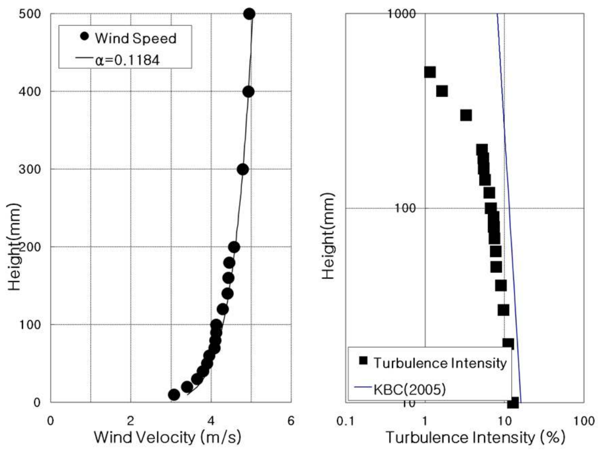


Figure 2: Vertical test wind velocity and turbulence intensity distribution

(a) 2D rectangular tower frame

(b) 3D rectangular tower frame

Figure 3: Wind tunnel test of the rectangular tower frame

2.3 Analysis of the test results

The solidity ratio that was used in the data analysis is the ratio of the wind protection member area within the internode area to the entire internode area. Eq. 1 shows the equation for this relationship:

$$\Phi = \frac{\sum_a}{A} \qquad (1)$$

wherein,

Φ = solidity ratio,

$\sum_a$ = wind protection member area within the internode area

A = internode area (= $\frac{(B_1 + B_2)/2}{2}$)

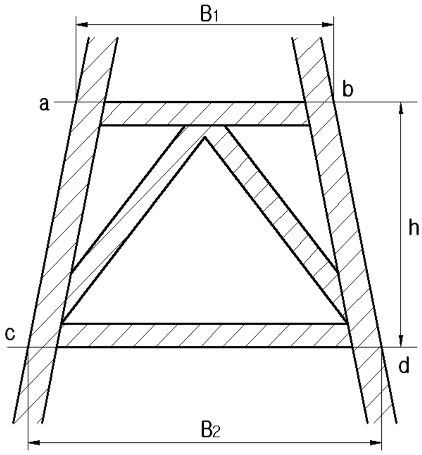


Figure 4: Solidity ratio of the frame

Eq. 2 was used to estimate the wind force coefficient in this test (Wind Engineering Institute of Korea, 1998 and Ohkuma Takeshi et al., 1996), as follows:

$$C = \frac{F}{q_H A} \qquad (1)$$

wherein, C = wind force coefficient;

F = aerodynamic force;

q_H = design velocity pressure (=); and

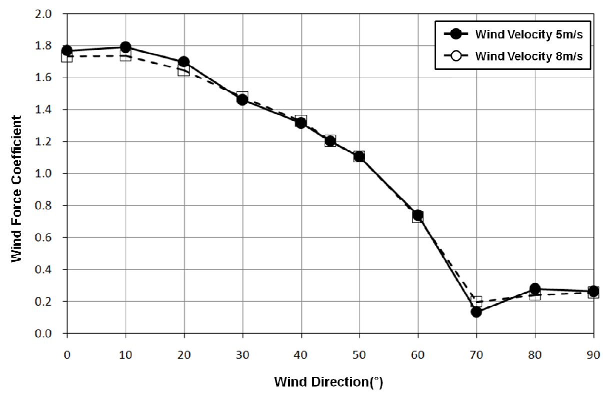
A = representative area (horizontal projected area at 0° wind direction).

3 EXPERIMENT RESULTS AND DISCUSSION

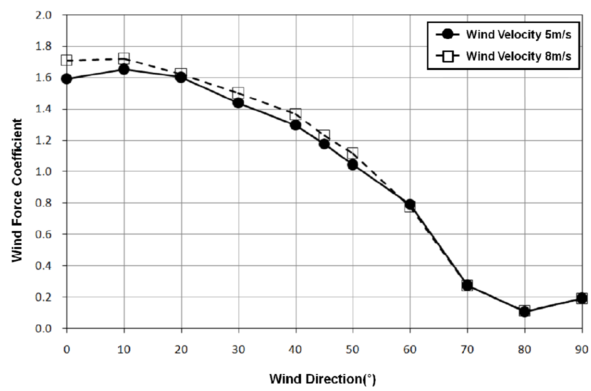
3.1 Wind force coefficient of the 2D rectangular tower frame

Fig. 5 shows the characteristics of the wind force coefficient of the 2D rectangular frame according to the wind direction angle. The wind force coefficient decreased with the increase in the wind direction angle in all of the 2D-type structures (Ⅰ, Ⅱ, and Ⅲ). In particular, the wind force coefficient was highest at the wind direction angle of 10° in all the 2D-type structures (Ⅰ, Ⅱ, and Ⅲ). With the gradual increase in the wind direction angle, the wind force coefficient also decreased and reached a minimum value at the wind direction angle of 80°. This is because as the wind direction angle increased, the projected area that was facing the wind became smaller than the reference representative area for wind force coefficient estimation (projected area at the 0° wind direction), and the wind force also decreased.

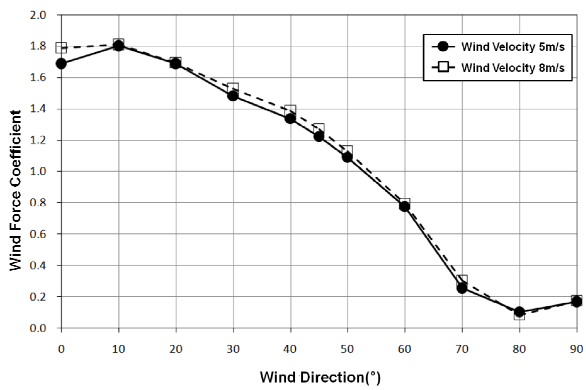
In the 2D-type structures I, II, and III, the solidity ratios of which increased by adding members to them, the solidity ratios were 0.117, 0.130, and 0.140, respectively. Thus, the change in the solidity ratio was very small, and it did not significantly influence the wind force coefficient. Table 2 shows the wind force coefficient of the 2D rectangular tower frame.



(a) 2D-type Ⅰ



(b) 2D-type Ⅱ



(c) 2D-type Ⅲ

Figure 5: Wind force coefficient according to the wind direction change in the 2D rectangular frame

Table 2: Wind force coefficient of the 2D rectangular tower frame

Wind Direction Angle	2D-type Ⅰ		2D-type Ⅱ		2D-type Ⅲ	
	5 m/s	8 m/s	5 m/s	8 m/s	5 m/s	8 m/s
0	1.77	1.73	1.59	1.71	1.69	1.79
10	1.79	1.74	1.65	1.72	1.80	1.81
20	1.70	1.65	1.60	1.63	1.69	1.70
30	1.46	1.48	1.44	1.50	1.48	1.53
40	1.32	1.33	1.30	1.37	1.34	1.39
45	1.21	1.21	1.18	1.23	1.22	1.27
50	1.11	1.11	1.05	1.12	1.09	1.13
60	0.74	0.73	0.79	0.78	0.78	0.79
70	0.14	0.20	0.28	0.27	0.26	0.30
80	0.28	0.24	0.11	0.11	0.10	0.08
90	0.26	0.25	0.19	0.19	0.17	0.18

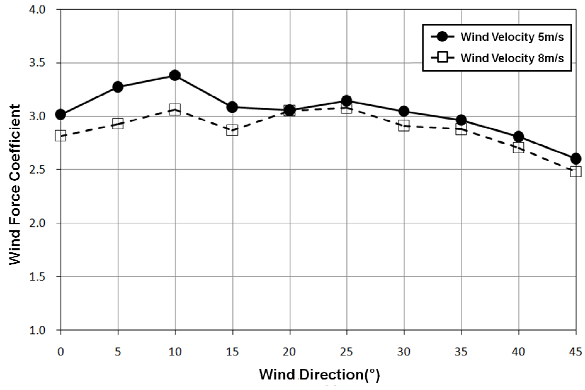
3.2 Wind force coefficient of the 3D rectangular tower frame

Fig. 6 shows the characteristics of the wind force coefficient of the 3D rectangular frame according to the wind direction angle. As shown in the 3D type I in Fig. 6 (a), the wind force coefficient, which was small at the wind direction angle of 0° and 45°, gradually increased with the increase in the wind direction angle, and started decreasing at the wind direction angle of 25°. The overall change in the wind force coefficient was not significant, though.

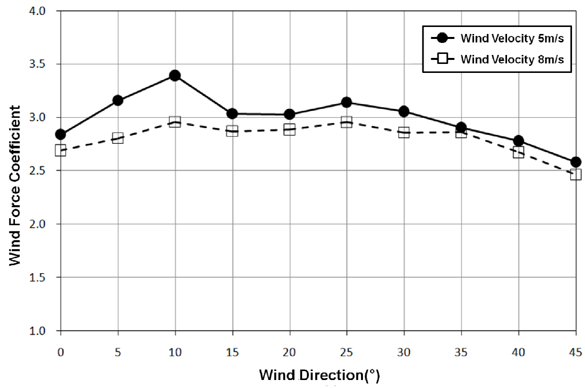
As with the 3D-type Ⅰ, the wind force coefficient, which was small at the wind direction angles of 0° and 45°, gradually increased with the increase in the wind direction angle, and started decreasing at the wind direction angle of 25°, as shown in the 3D-type Ⅱ in Fig. 6 (b).

In the 3D-types Ⅲ, Ⅳ, and Ⅴ, the wind force coefficient decreased with the increase in the solidity ratio, as shown in Fig. 6 (c) - (e). The wind force coefficient did not significantly change when the wind direction changed, however, as in 3D type Ⅰ.

The wind force coefficient slightly increased at the 5m/s wind speed and the direction angles of 5° and 10° in the 3D-type Ⅰ (solidity ratio: 0.117) and the 3D-type Ⅱ (solidity ratio: 0.130), whose member sizes were small. On the whole, however, the wind force coefficient gradually increased with the increase in the wind direction angle, and started decreasing at the wind direction angle of 25°. The overall change in the wind force coefficient was not significant.



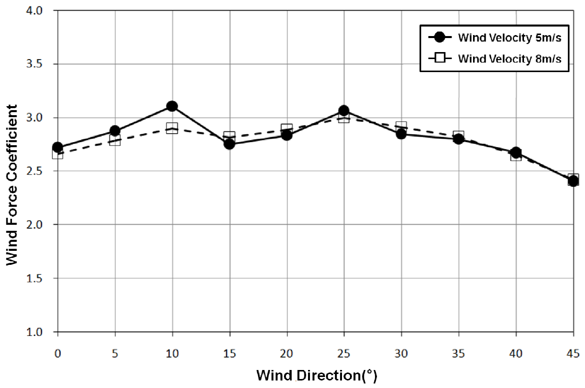
(a) 3D-type Ⅰ



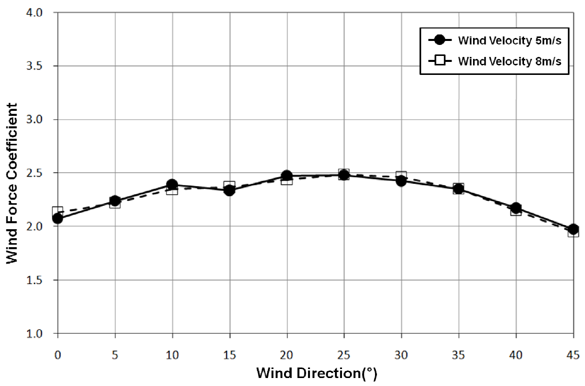
(b) 3D-type Ⅱ

Table 3: Wind force coefficient of the 3D rectangular tower frame

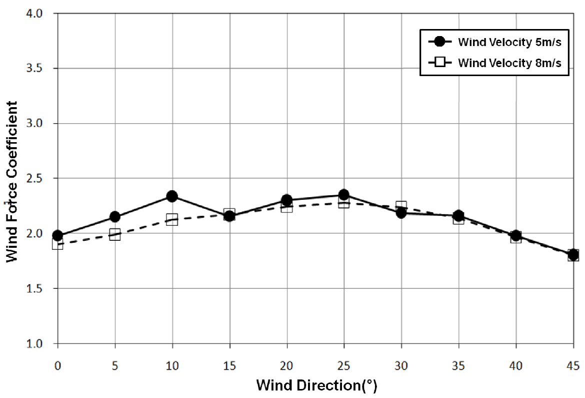
Wind Direction Angle	3D-type Ⅰ		3D-type Ⅱ		3D-type Ⅲ		3D-type Ⅳ		3D-type Ⅴ	
	5 m/s	8 m/s	5 m/s	8 m/s	5 m/s	8 m/s	5 m/s	8 m/s	5 m/s	8 m/s
0	3.02	2.82	2.84	2.69	2.73	2.66	2.08	2.13	1.98	1.90
5	3.27	2.93	3.16	2.81	2.88	2.79	2.24	2.22	2.15	1.99
10	3.38	3.06	3.39	2.96	3.11	2.90	2.39	2.35	2.34	2.13
15	3.09	2.87	3.03	2.87	2.75	2.82	2.34	2.37	2.16	2.17
20	3.06	3.06	3.03	2.89	2.84	2.89	2.48	2.44	2.30	2.24
25	3.14	3.08	3.14	2.96	3.06	3.00	2.48	2.49	2.35	2.28
30	3.05	2.91	3.06	2.86	2.85	2.91	2.43	2.46	2.19	2.24
35	2.96	2.88	2.91	2.86	2.80	2.83	2.35	2.35	2.16	2.14
40	2.81	2.71	2.78	2.67	2.67	2.65	2.17	2.15	1.98	1.97
45	2.60	2.48	2.58	2.47	2.41	2.42	1.98	1.95	1.81	1.80



(c) 3D-type Ⅲ



(d) 3D-type Ⅳ



(e) 3D-type Ⅴ

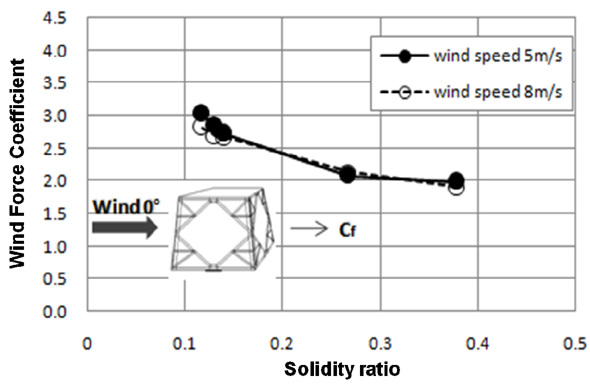
Figure 6: Wind force coefficient according to the wind direction change in the 3D rectangular frame

Fig. 7 shows the characteristics of the wind force coefficient of the 3D rectangular frame according to the change in the solidity ratio for different wind direction angles. In this study, only three wind direction angles were assumed: 0°, 25°, and 45°.

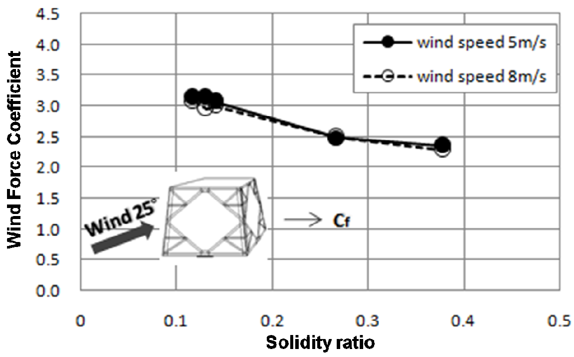
For the wind direction angle of 0°, the wind force coefficient gradually decreased as the solidity ratio increased from 0.117 to 0.378, as shown in Fig. 7 (a). The decrease in the wind force coefficient was not significant for the solidity ratios of 0.117, 0.130, and 0.140, which were increased by adding members to the basic structure, because the change in the solidity ratio was small. For the solidity ratios of 0.267 and 0.378, which were increased by changing the member size, the decrease in the wind force coefficient was large due to the large change in the solidity ratio. This trend was the same for both the 5m/s and 8m/s wind velocities. For the wind directions of 25° and 45°, the wind force coefficient also decreased with the increase in the solidity ratio, as with the wind direction of 0° that is shown in Fig. 10 (b) and (c). This trend was the same for all wind direction angles.

Table 3 shows the wind force coefficients for five 3D rectangular frame types. The wind force coefficient was set at 8 m/s to ensure a stable condition. In the 3D-type Ⅰ, the maximum wind force coefficient was 3.08 at the wind direction angle of 25°, and the minimum was 2.48 at 45°. In the 3D-type Ⅱ, the maximum wind force coefficient was 2.96 at the wind direction angles of 10° and 25°, and the minimum was 2.47 at 45°. In the 3D-type Ⅲ, the maximum wind force coefficient was 3.00 at the wind direction angle of 25°, and the minimum was 2.42 at 45°. In the 3D-type Ⅳ, the maximum wind force coefficient was 2.49 at the wind direction angle of 25°, and the minimum was 1.95 at 45°. In the 3D-type Ⅴ, the maximum wind force coefficient was 2.35 at the wind direction angle of 25°, and the minimum was 1.80 at 45°.

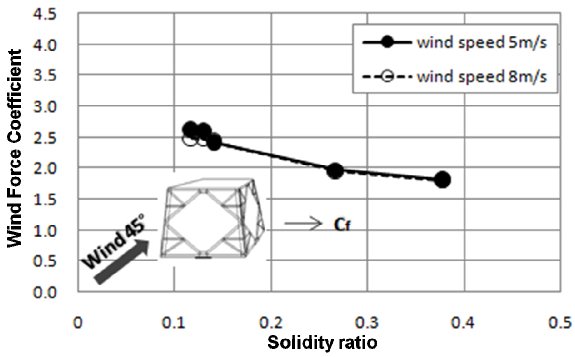
In summary, the deviation of the wind force coefficient was 0.6 in the 3D-type Ⅰ, 0.49 in the 3D-type Ⅱ, 0.58 in the 3D-type Ⅲ, 0.54 in the 3D-type Ⅳ, and 0.55 in the 3D-type Ⅴ. The overall trend of the wind force coefficient according to the wind direction angle did not significantly vary according to the change in the wind direction angle.



(a) Wind direction angle of 0°



(b) Wind direction angle of 25°



(c) Wind direction angle of 45°

Figure 7: Wind force coefficient according to the solidity ratio of the 3D rectangular frame

3.3 Comparison of the domestic standard with the wind tunnel test results

In this study, the wind force coefficient test for the rectangular tower frame was limited to the angle steel members. To compare the test results with the standard, the following wind force coefficient equations for angle steel in the KEPCO design standard (DS-1111) and the Korea Building Code were used. The equation in the KEPCO Design Standard (DS-1111) is currently used when the tower body wind force coefficients of square lattice towers or steel poles are calculated using the solidity ratio (Eq. 3).

$$C = 4.0 - 6.6\phi + 5.5\phi^2 \quad (3)$$

Eq. 4 is the equation for calculating the wind force coefficient using the solidity ratio of the square plane of the truss tower, in the Korea Building Code (Eq. 4).

$$C_f = 4.0\xi^2 - 5.9\xi + 4.0 \quad (4)$$

Fig. 8 shows the wind tunnel test results compared with the wind force coefficient according to the solidity ratio of the Korea Building Code and KEPCO Design Standard (DS-1111).

Fig. 8 shows the wind force coefficient values according to the equations for the truss tower in the Korea Building Code and for the tower frame in the KEPCO Design Standard (DS-1111), compared with the wind force coefficient measurements from the wind tunnel test in this study. On the whole, the values from the KEPCO Design Standard (DS-1111) and Korea Building Code were slightly larger than the measurements from the test. This seems to have been because the design standard and building code were more conservatively determined.

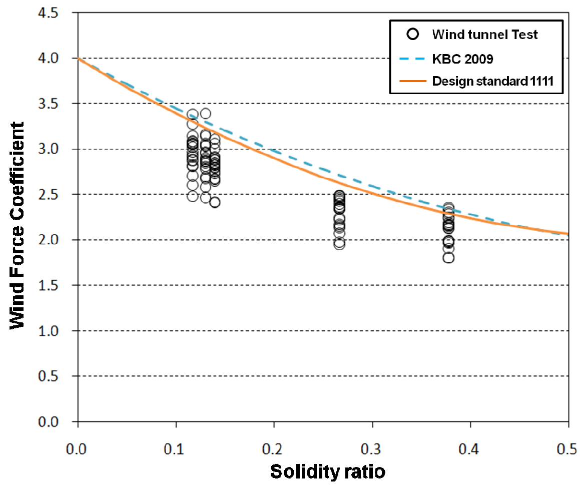


Figure 8: Comparison of the domestic standard with the wind tunnel test results

4 CONCLUSION

To evaluate the wind force coefficient characteristic of the rectangular tower frame, three 2D and five 3D models were manufactured by varying the basic members and solidity ratios. The wind tunnel test results with different wind direction angles are summarized as follows.

(1) According to the wind direction change, the wind force coefficient gradually increased within the wind direction range of 0-25°, and then decreased. the overall change in the wind force coefficient was about 0.5, however, which was not significant.

(2) The wind force coefficient values from the KEPCO Design Standard (DS-1111) and the Korea Building Code are 10.7% larger than the measurements from the test on the average. This seems to have been because the standards were determined to ensure the structures' safety.

In this study, the rectangular frame members of the 2D and 3D test models were limited to the angle steel, and only five types of solidity ratios were used. Because other member types such as steel pipes are used to construct towers, including truss towers, further studies must be conducted on diverse member shapes and solidity ratios.

5 REFERENCES

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