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Serviceability evaluation methods for high-rise structures considering wind direction

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Abstract. High-rise buildings are very slender and flexible. Their low stiffness values make them vulnerable to horizontal loads, such as those associated with wind or earthquakes. For high-rise buildings, the threat to serviceability caused by wind-induced vibration is an important problem. To estimate the serviceability under wind action, the response acceleration of a building at the roof height is used. The response acceleration is estimated by the same wind speed at all wind directions. In general, the effect of wind direction is not considered. Therefore, the response accelerations obtained are conservative. If buildings have typical plans and strong winds blow from relatively constant wind directions, it is necessary to account for the wind direction to estimate the response accelerations. This paper presents three methods of evaluating the response accelerations while considering the effects of wind direction. These three serviceability evaluation methods were estimated by combining the wind directional frequency data obtained from a weather station with the results of a response analysis using wind tunnel tests. Finally, the decrease in the efficiencies of the response acceleration for each serviceability evaluation method was investigated by comparing the response acceleration for the three methods accounting for wind direction with the response acceleration in which wind direction was not considered.

Keywords: serviceability evaluation method; Weibull parameter; wind directional frequency

1. Introduction

A Seventy percent of Korea's topography consists of mountainous areas, and because of its geographical characteristics, the number of skyscrapers is increasing to accommodate large populations. High-rise buildings tend to be built with lightweight material because higher buildings lead to greater weight. Consequently, the stiffness is lowered, leaving them very vulnerable to horizontal loads such as those generated by wind and earthquakes (The Wind Engineering Institute of Korea 2010). Generally, the greater the height, the smaller the influence of the earth's surface and the stronger the effect of the wind. Therefore, high-rise buildings with low stiffness and slender shape are more sensitive to wind-induced vibration. Because of these complex effects, wind-induced vibrations in high-rise buildings have become a very important consideration in structural design and serviceability.

When a building vibrates on account of strong winds, occupants in the building feel discomfort. In the "Korea Building Code (2016)" (abbreviated as KBC-2016), the evaluation of the serviceability of the building for these occupants is referred to as a serviceability evaluation, and the acceleration of the building is used as a measure of the evaluation (Architectural Institute of Korea 2016). The response acceleration of a building with square and rectangular shape can be calculated using the formula and dynamic characteristics (e.g., mass, damping ratio, frequency) of KBC-2016. However, it is difficult to predict the behavior of high-rise buildings that are slender and irregularly shaped, so wind-induced responses are evaluated through wind tunnel tests. At this time, the wind tunnel test is conducted under the assumption that the identical wind speed is applied in all wind directions, and the response acceleration is calculated. However, this assumption is somewhat conservative because actual winds have different frequencies depending on the wind direction, and wind speeds vary according to direction.

For example, Fig. 1 is a graph of the response acceleration in terms of wind direction for any high-rise structures. In this figure, dotted lines represent the ISO standards and ● represent the response acceleration of a building in each wind direction, calculated on the assumption that the same wind is blowing in all wind directions. In this graph, an angle of 0° is assumed for north. The response acceleration in the N-direction exceeds the ISO standard. Looking at Table 1, the frequency of wind speed in the N-direction is 0.01%, which indicates that wind is almost not blowing. The N-direction results in the response acceleration exceeding the ISO standard, even though the wind is hardly blowing. Therefore, in the case of the N-direction, the response acceleration is overestimated. However, the frequency of wind speed alone cannot assess the wind's climate. For example, if the wind speed of a low frequency wind is very strong, the strong wind speed of that

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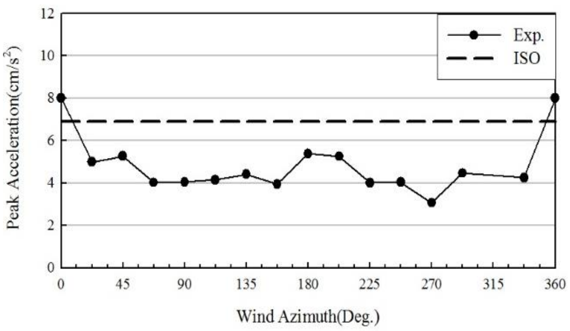


Fig. 1 ex) Response acceleration by wind direction

Table 1 Wind directional frequency

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE
Frequency(%)	0.01	0.19	5.37	14.32	1.42	0.25	0.47	0.49
Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW
Frequency(%)	0.36	3.18	13.69	12.38	22.02	19.93	4.30	16.4

wind cannot be ignored. Therefore, serviceability should be evaluated through probability distribution combining frequency and wind speed. In view of these examples, it is necessary to evaluate the serviceability by considering the wind directional frequency and wind speed for a rational structural design.

The method of evaluating the serviceability of a building varies from country to country. In National Research Council Canada(NRCC) (2015), a 10-year return period wind speed is used, and the same level of response acceleration criteria is adopted across all frequency bands (National Building Code of Canada (NBCC 2005). Architectural Institute of Japan(AIJ) (2015) uses a 1-year return period wind speed and unlike NBCC, a standard for the response acceleration is adopted, based on the frequency band, while a method for considering the wind directional frequency is proposed (Architectural Institute of Japan 2015). The International Organization for Standardization(ISO) (2007) has adopted the serviceability evaluation method of the AIJ, basing the standard of the response acceleration on the frequency band (International Organization for Standardization 10137(ISO 10137) 2007). Architectural Institute of Korea(AIK) (2016), does not provide clear criteria for serviceability evaluation but recommends that "residents should not feel uneasy and uncomfortable" and encourages the use of the ISO standard (Korean Building Code(KBC) 2016). The Japan Association for Wind Engineering (2007) suggests a method for evaluating the response acceleration based on wind directional frequency, using wind tunnel test results and probability distribution (Wind Engineering Handbook 2007). In addition, a number of studies have been conducted on serviceability (Adrian 2018, Pagnini and Solari 1998, Lamb and Kwok 2017, Kwok *et al*. 2009, Johann *et al*. 2015). Adrian (2018) has developed a procedure to evaluate the response acceleration of tall buildings, taking into account wind climate, structural characteristics, and perception of motion and maximum response to complement various criteria and standards. Pagnini and Solari (1998) described the link between acceleration due to wind and structural damping, and suggested the problem and improvement. Lamb and Kwok (2017) described seven elements that could advance the next generation of serviceability design criteria that would increase the fundamental understanding of human responses to building action. Kwok *et al*. (2009) said vibration is a subjective perception of humans. In addition, since there is no design standard that can be evaluated internationally, studies on the vibration of buildings in the past and human perceptions have been reviewed, and a reasonable standard law has been proposed. Johann *et al*. (2015) says that integration of the standard codes for evaluating serviceability is necessary, and that education and comfort evaluation are needed so that future users can recognize and respond to the building's action. However, the above studies focus on the standard of serviceability evaluation and human response, and there are not many studies on the serviceability evaluation of buildings according to the combined distribution of wind direction frequency and wind speed intensity.

For building in places other than Japan, it only provides criteria for response acceleration for a serviceability evaluation but does not address serviceability evaluation methods that consider wind directional frequency. However, Japan has proposed only a model that can evaluate the acceleration by combining the frequency of wind direction and the distribution of wind speed, but it does not indicate the relationship between the response of the building and the characteristics and frequency of the wind speed in the building. Also, it is not shown how to estimate the wind speed corresponding to the response acceleration.

In this paper, three rational serviceability evaluations combining Weibull parameters and wind directional frequency were proposed to compensate for the deficiencies of current serviceability evaluations used in each country, using a Weibull distribution suitable for estimating the 1-year return-period wind speed.

2. Research method

2.1 Wind frequency and weibull parameter

To evaluate the serviceability of a building, considering the wind directional frequency, it is necessary to obtain the wind directional frequency and Weibull parameter. In this study, the wind directional frequency and Weibull parameter of a specific region were calculated based on the method of Ha and Kim (2002). The probability distribution of daily maximum wind speed is known to approximate Gumbel distribution or Weibull distribution (Counihan 1975, Shin *et al*. 2018). According to studies by Japan and USA, the distribution of daily maximum wind speed is generally known to follow the Weibull distribution (Architectural Institute of Japan 2004, Cook 1985). The data used to calculate the wind directional frequency and Weibull parameters were the daily maximum wind speeds, which were suitable for estimating the 1-year return-period wind

Table 2 Directional wind speed due to response acceleration

cm/s^2	Wind speed by wind direction (m/s)															
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
0.1	1.4	1.7	1.4	1.8	1.2	1.2	1.3	1.2	1.2	1.1	1.4	1.5	1.4	1.4	1.5	1.6
0.2	2.0	2.4	2.0	2.5	1.7	1.7	1.9	1.7	1.7	1.6	2.0	2.1	2.0	2.0	2.2	2.2
0.3	2.4	3.0	2.4	3.0	2.1	2.1	2.3	2.1	2.1	2.0	2.4	2.5	2.4	2.5	2.7	2.7
:								:								
:								:								
99.8	43.6	54.6	44.6	55.4	37.7	37.5	42.2	38.3	37.9	35.8	43.6	46.0	44.0	45.6	48.5	49.6
99.9	43.7	54.7	44.6	55.4	37.7	37.5	42.2	38.3	38.0	35.8	43.6	46.0	44.0	45.7	48.5	49.6
100	43.7	54.7	44.6	55.5	37.7	37.6	42.2	38.3	38.0	35.8	43.6	46.1	44.0	45.7	48.5	49.6

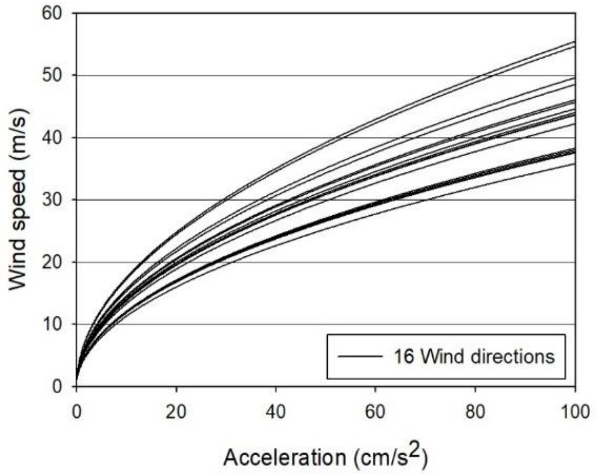


Fig. 2 Directional wind speed due to response acceleration

speed (Kang and Ko 2018, Kim 2017), and the data were provided by the Korea Meteorological Administration. And wind speed was homogenized with wind speed of 10 m high on the surface of ground surface roughness C (KBC 2016, Helliwell 1971, Sutton 1950, Jacson 1981).

Data from 2006 to 2015 were considered. The wind data provided by the Korea Meteorological Administration were provided in 16 directions, including N, NNE, NE, ENE, E, ESE, SE, SSE, SSW, SW, WSW, W, WNW, NW, and NNW.

In the study, the daily maximum wind speed for 10 years was divided into the 16 wind directions, and statistical processing was performed. The wind directional frequency and Weibull parameter for each wind direction were calculated. The wind directional frequency A_j is the ratio of the number of daily maximum wind speeds over 10 years in the region N_A to the number of daily maximum wind speeds in each wind direction, as shown in the following equation.

$$A_j = \frac{N_j}{N_A} \times 100(\%) \tag{1}$$

2.2 Serviceability evaluation methods considering wind directional frequency

The serviceability evaluation through the wind tunnel test is based on the assumption that the same wind speed is generated in all wind directions. This assumption has the advantage of relative simplicity and safe design. However, the wind is not the same in all directions because of the dry northwesterly wind in winter, caused by a three cold days/four warm days cycle, and the Typhoon-like conditions of high temperature and humidity in summer. Therefore, it is reasonable and economical to base the serviceability design of buildings on the wind directional frequency.

2.2.1 Method by the response of the building (MRB)

Wind tunnel tests are carried out with the assumption that the same wind speed is applied in all wind directions. However, even though wind speeds are the same for each direction, the response acceleration varies depending on the shape of the plane and the dynamic characteristics. The MRB (method by the response of the building) assumes that after a general wind tunnel test, the same response acceleration occurs for all wind directions as opposed to the existing assumptions. Because the response accelerations are different in each wind direction for isotropic wind speeds, the speed of the wind that will generate the assumed response acceleration will be different in each wind direction if the response acceleration is assumed to be the same. In this method, the wind speed is calculated for each wind direction according to the response acceleration level. In this study, the response acceleration is assumed to vary from 0.1 cm/s^2 - 100 cm/s^2, and the wind velocity for the wind direction, which generates the assumed response acceleration, is calculated as shown in Table 2 and Fig. 2.

In the conventional method, the wind tunnel test is performed, and the response acceleration is calculated using the spectral modal analysis method for first vibration mode (Ding and Zhu 2017, Cui and Caracoglia 2017, Zhang *et al*. 2015, Xu *et al*. 2014). Conversely, to calculate the wind speed using the response acceleration, it is necessary to reverse the analysis process of the spectral modal analysis method. To perform an inverse analysis on the wind speed through the spectral modal analysis method, various factors are used. Elements that are fixed according to the wind direction are the frequency, mass, damping ratio, width, height of the building, peak factor, spectral coefficient of the model, and the coefficient of variation moment. The peak factor, spectral coefficient of the model, and coefficient of variation moment can be obtained through wind tunnel tests. These factors are used to generate different accelerations depending on the wind direction. These factors can be used to invert the wind speed according to the response acceleration level. The equation for calculating the response acceleration of X-dir, Y-dir and Z-dir through the spectral modal analysis method is as follows (KBC 2016, Wind-Resistant Engineering 2010).

The method of spectral modal analysis based on the power spectrum density of the variable wind power obtained from the wind tunnel test (High Frequency Force Balance) is as follows.

$$X_{max} = \overline{X} + g_x \bullet \sigma_x \tag{2}$$

The following are the equations of motion of structures under random external forces.

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = F(t) \tag{3}$$

If the first vibration mode of a building is dominant, the displacement of the building can be represented by generalized displacement and vibration mode.

$$x(z,t) = \mathrm{X}_1(t) \cdot \mu_1(z) \tag{4}$$

where $\mathrm{X}_1(t)$ is Generalized Displacement for first vibration mode, $\mu_1(z)$ is first vibration mode.

Therefore, the following equations of motion for generalized displacement can be obtained.

$$M_1\ddot{X}_1(t) + C_1\dot{X}_1(t) + K_1X_1(t) = F_1(t) \tag{5}$$

After Fourier transform of both sides of Eq. 5, The power spectrum density of the variable displacement can be determined by the power spectrum density and the mechanical admittance of the variable wind force.

$$S_{x1}(n) = \left|H_r(n)\right|^2 \cdot S_{F1}(n) \tag{6}$$

Where

$$\left|H_r(n)\right|^2 = \frac{1}{K_1^{\,2}\left[\left\{1-(n/n_1)^2\right\}^2 + 4\zeta_1^{\,2}\cdot(n/n_1)^2\right]}$$

Therefore, the variance of the generalized displacement σ_x^2 is given by

$$\sigma_x^{\,2} = \int_0^\infty S_{x1}(n)dn = \int_0^\infty \left|H_r(n)\right|^2 S_{F1}(n)dn \tag{7}$$

If first vibration mode is set to $\mu_1(z)$=z/H, the generalized wind power is given by

$$F_1(t) = \int_0^H f(z,t)\frac{z}{H}dz = \frac{1}{H}M(t) \tag{8}$$

The power spectrum density of the generalized external force $S_{F1}(n)$ through the base shear force can be changed to the power spectrum density of the overturning moment $S_M(n)$ as follows

$$S_{F1}(n) = \frac{1}{H^2}S_M(n) \tag{9}$$

By substituting Eq. 9 into Eq. 7, the variance of the generalized displacement σ_x^2 can be obtained.

$$\begin{aligned}\sigma_x^{\,2} &= \int_0^\infty S_{x1}(n)dn = \int_0^\infty \left|H_r(n)\right|^2 S_{F1}(n)dn \\ &= \frac{1}{H^2}\int_0^\infty \left|H_r(n)\right|^2 S_M(n)dn\end{aligned} \tag{10}$$

From the above equation, it can be expressed as follows by substituting n_1, ζ_1, M_1, the characteristic value of the building.

The integral of the power spectrum of the response displacement is divided into the resonance R_f and non-resonance B_f parts and can be approximated as follows

$$\begin{aligned}\sigma_x &= (B_f + R_f)^{1/2} \\ &= \left[\frac{\sigma_M^{\,2}}{(2\pi n_1)^2 M_1)^2\cdot H^2} + \frac{\pi n_1\cdot S_M(n_1)}{4\zeta_1\cdot((2\pi n_1)^2 M_1)^2\cdot H^2}\right]^{1/2}\end{aligned} \tag{12}$$

The standard deviation of the response acceleration can be expressed as

$$\begin{aligned}\sigma_\alpha &= (R_f)^{1/2}\cdot(2\pi n_1)^2 \\ &= \left[\frac{\pi n_1\cdot S_M(n_1)}{4\zeta_1\cdot((2\pi n_1)^2 M_1)^2\cdot H^2}\right]^{1/2}\cdot(2\pi n_1)^2\end{aligned} \tag{13}$$

Therefore, the maximum response acceleration can be calculated by multiplying the peak factor g by Eq. 13.

$$\alpha_{\max} = g\cdot\sigma_\alpha \tag{14}$$

The wind speed corresponding to the response acceleration can be calculated as follows by inverse analysis of the Eq. 13 and 14.

$$\sigma_\alpha = \frac{\alpha_{\max}}{g} \tag{15}$$

$$R_f = \left(\frac{\sigma_\alpha}{(2\pi n)^2\cdot 100}\right)^2 \tag{16}$$

$$[n_1 S_M(n_1)]_{full} = \frac{R_f\, 4\zeta((2\pi n)^2 M_1)^2 H^2}{\pi} \tag{17}$$

$$\sigma_m = \left(\frac{[(n_0 S_M(n_0))/\sigma_M^{\,2}]_{model}}{[n_1 S_M(n_1)]_{full}}\right)^{1/2} \tag{18}$$

$$V_H = \left(\frac{16\sigma_m}{\left|C_{my}{}'\right| BH^2}\right)^{1/2} \tag{19}$$

where σ_α is the standard deviation of the response acceleration, $\alpha_{\max}$ is the maximum response acceleration, g is the peak factor, R_f is the resonance coefficient, $S_M(n_1)$ is the overturning moment spectrum of the building, ζ is the damping ratio, M_1 is the generalized mass, H is the reference height, σ_m is the standard deviation of the overturning moment, $[(n_0 S_M(n_0))/\sigma_M^2]_{\text{model}}$ is the spectral coefficient of the model, V_H is the design wind speed, $C_{my}{}'$ is the coefficient of the variation moment, and B is the representative width.

The standard deviation of the response angular acceleration on the Z-dir can be obtained by using the spectral modal analysis as follows.

$$\alpha_{\theta\max} = g\cdot\sigma_{\theta_\alpha}$$

$$= g\cdot\left[\frac{\psi\sigma_T}{I_1}\cdot\left(\frac{\pi}{4\zeta_1}\cdot\frac{n_1\cdot S_T(n_1)}{\sigma_T{}^2}\right)\right]^{1/2} \tag{20}$$

The response acceleration on the Z-dir can be obtained as follows using the response acceleration of the X-dir and the Y-dir and the outermost distance of the building from the center of mass (Nist 2014).

$$\alpha_{T\max} = \sqrt{(\alpha_{x\max} - D_y\cdot\alpha_{\theta\max})^2 + (\alpha_{y\max} - D_x\cdot\alpha_{\theta\max})^2} \tag{21}$$

The wind speed corresponding to the response angular acceleration can be calculated as follows by inverse analysis of the Eq. 20.

$$\sigma_T = \frac{\sigma_{\theta_\alpha} I_1}{9.81\cdot\psi\cdot\sqrt{\frac{\pi}{4\zeta_1}\cdot\left(\frac{n_0 S_T(n_0)}{\sigma_T{}^2}\right)_{\text{model}}}} \tag{22}$$

$$V_H = \left(\frac{16\sigma_T}{|C_{mz}{}'|BDH}\right)^{1/2} \tag{23}$$

where $\sigma_{\theta\alpha}$ is the standard deviation of the response angular acceleration, $\alpha_{\theta max}$ is the maximum response angular acceleration, ψ is correction coefficient for mode shape, σ_T is standard deviation of torsional moment, I_1 is generalized mass moment of inertia.

KBC2016 K_{zr}, K_{zt} and I_w were used to convert the design wind speed according to the ground surface roughness according to different wind direction into the basic wind speed. And the basic wind velocity was standardized by 10m ground surface roughness C, which is the height of meteorological observatory (KBC 2016).

$$V_0 = \frac{V_H}{K_{zr}K_{zt}I_w} \tag{24}$$

Where V_0 is the basic wind speed, K_{zr} is the velocity pressure exposure coefficient, K_{zt} is the terrain surcharge coefficient, and I_w is the importance factor.

It is known that the excess probability of the wind speed by wind direction can be predicted by the Weibull distribution, which is a probability distribution (Ha and Kim 2002). The excess probability of the wind speed is calculated through the Weibull parameter in an arbitrary direction i and multiplied by the frequency to calculate the excess probability of the wind speed with respect to an arbitrary wind direction (You 2018, Murukami *et al*. 1983). The probability of exceeding the wind speed with respect to the total wind direction can be obtained by summing the excess probabilities of all the wind directions $P(>V)$.

$$P(>V) = \sum_{i=1}^{16} A_i \times e^{-\left(\frac{V}{c_i}\right)^{k_i}} \tag{25}$$

Where c_i, k_i is the Weibull parameter for each wind direction, and A_i is the frequency for each wind direction.

In this study, the wind speed corresponding to the response acceleration level varies according to wind direction, so it is necessary to calculate the excess probability using different wind speeds for each wind direction. Thus, the probability of exceeding the response acceleration for the entire wind direction $P(>\alpha_{max})$ is given by

$$P(>\alpha_{\max}) = \sum_{i=1}^{16} A_i \times e^{-\left(\frac{V_i}{c_i}\right)^{k_i}} \tag{26}$$

Here, V_i is the wind speed for each wind direction that generates the response acceleration α_{max}.

Eq. (27) gives the relationship between the excess probability corresponding to the response acceleration and the return period. Since the daily maximum wind speed is used in this study, the unit of the return period should be converted from year to day. Therefore, the relation between the excess probability based on the daily maximum wind speed $P(>\alpha_{max})$ and the return period T can be expressed as Eq. 28.

$$P(>\alpha_{\max}) = \frac{1}{T} \tag{27}$$

$$365T = \frac{1}{P(>\alpha_{\max})} \tag{28}$$

The return period can be calculated according to the response acceleration level through Eq. 28. Fig. 3 shows the return period as a function of the response acceleration.

In this figure, the Y-axis value is the 1-year return-period response acceleration, considering the wind direction frequency.

2.2.2 Method by estimation of wind speed by wind direction (MWD)

The actual wind blows with different frequency and intensity for each wind direction.

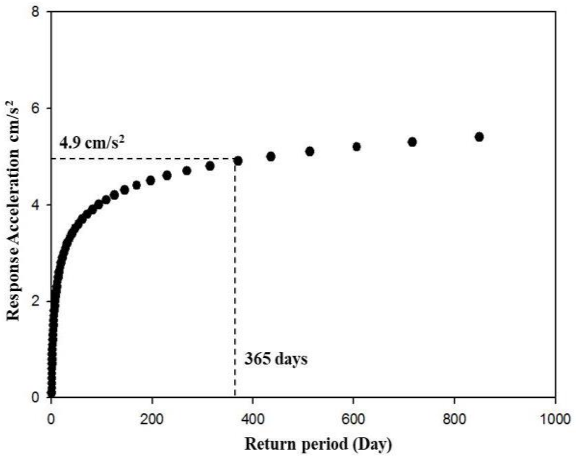


Fig. 3 1-year return period response acceleration graph

If this real wind characteristic is reproduced and applied to the wind tunnel test, the method will have a remarkably high reliability. However, considerable amounts of time and effort are needed to reproduce real wind characteristics in wind tunnel tests. MWD (method by estimation of wind speed by wind direction) can improve the reliability of analysis by using the wind speed by wind direction and conduct experiments with one wind speed.

The daily maximum wind speed is suitable for estimating the wind speed of such a short return period as one year. According to studies by Japan, USA, and Korea, it is well known that it corresponds well with the Weibull distribution. The excess probability of the Weibull distribution is given in the following equation.

$$P(V) = e^{-\left(\frac{V}{c}\right)^k} \tag{29}$$

The relation between the return period and the excess probability is as shown in Eq. 27. Eqs. 27 and 29 can be used to calculate the wind speed according to the return period. The maximum wind speed classified by wind direction and the Weibull parameter by wind direction can be used to calculate the 1-year wind speed by wind direction as follows.

$$V_i(T) = c_i \cdot [\ln(365T)]^{\frac{1}{k_i}} \tag{30}$$

Here, c_i, k_i is the Weibull parameter for each wind direction, and T is the return period.

The expression for reducing the level of the return period by multiplying by the frequency in the return period in the same manner as Eq. 26 can be expressed as follows.

$$V_{i,A}(T) = c_i \cdot [\ln(A_i \cdot 365T)]^{\frac{1}{K_i}} \tag{31}$$

Here, A_i is the frequency for each wind direction, and $V_{i,A}$ is the 1-year return-period wind speed for each wind direction, considering wind directional frequency. An example is shown in Table 3 below.

Table 3 1-year return period wind speed by each winddirection in Busan (m/s)

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE
Wind speed	12.2	11.5	9.5	6.2	6.5	6.9	7.2	9.7
Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW
Wind speed	10.8	13.5	17.2	13.6	13.3	12.5	8.4	11.5

Response analysis is performed by multiplying the actuality time, length, and wind speed by simulating the conditions of the wind tunnel test on real objects and making the data non-dimensional through the law of dynamical similarity. The MWD method uses a 1-year return-period wind speed by wind direction, considering the frequency of each wind direction in the process of conducting an experiment with a single wind speed, and then performing a response analysis. Then, the response acceleration is calculated by simulating the wind tunnel experimental data obtained with one wind speed, using different conditions under the law of dynamical similarity, according to the actual wind speeds for each wind direction. The maximum response acceleration of the wind direction is presented as a 1-year return-period response acceleration, which represents the target building.

2.2.3 Method by acceleration and wind directional frequency (MAF)

Unlike the previous methods, the serviceability evaluation method of this section is a method of evaluating the building serviceability by applying the wind directional frequency directly to the acceleration, rather than applying the wind frequency to the wind speed. Wind tunnel testing assumes that the same 1-year return-period wind speed is generated for all wind directions and performs wind tunnel testing at a single wind speed to calculate the response acceleration of the entire wind direction. In this case, assuming that the response acceleration for each wind direction is influenced by the frequency of each wind direction, its value can be expressed as follows.

$$\alpha_{\max,i,A} = A_i \cdot \alpha_{\max.i} \tag{32}$$

where A_i is the frequency of wind direction and α_{maxi} is the response acceleration of wind direction.

As shown in Eq. (32), the level of the response acceleration can be reduced by multiplying the response acceleration for a given wind direction by the wind directional frequency, and the response acceleration of the wind direction based on the wind directional frequency can be calculated by the following equation.

$$\alpha_{\max} = \sum_{i=1}^{16} A_i \cdot \alpha_{\max,i} \tag{33}$$

As shown in Eq. (33), the response accelerations of all wind directions can be summed up to calculate the 1-year return-period response acceleration, considering the wind direction frequency.

3. Results

To compare the above three serviceability evaluation methods, the wind tunnel test data of buildings located in Daegu and Busan in Korea and Weibull parameters, as a function of wind direction and wind directional frequency, from Daegu and Busan were used. The surface roughness around the target building is shown in Fig. 4. The Weibull distribution characteristics of the target area are shown in Table 4, W.D. means wind direction, A_i refers to wind directional frequency, and c_i, k_i refers to Weibull parameter. In case of Daegu, the W-direction is predominant, and in Busan, the NNE- and NNW-directions dominate. The wind directions of the wind tunnel test varied from 0° to 337.5°, the same directions as provided by the Meteorological Agency. The X-axis of the building is assumed to be 0° in the experiment, with angles increasing in a counterclockwise direction, and 0° is assumed to be the N-direction. The plane shape of the target building is shown in Fig. 5, and the heights of the buildings considered are 112 m and 166 m. The detailed dynamic characteristics of the two buildings are shown in Table 5.

The estimated 1-year return-period wind speed of Daegu and Busan is estimated as the Weibull distribution. The response acceleration is calculated at the same wind speed for all wind directions using the estimated wind speed of Daegu, 11.51 m/s, and Busan, 15.57 m/s. Fig. 6 shows the response acceleration.

3.1 Method by the response of building (MRB)

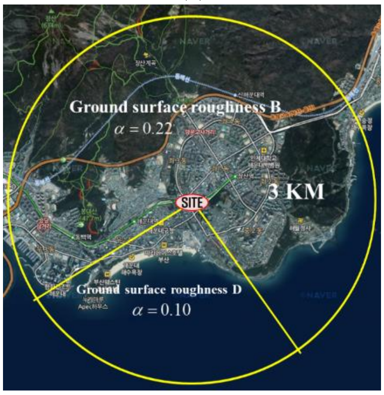
The response accelerations calculated using the same wind speed for all wind directions and the 1-year return-period response acceleration calculated using the MRB method are shown in Figs. 7 and 8.

In Daegu buildings, the X-axis decreased by 59%, the Y-axis decreased by 35% and Z-axis decreased by 35%, and in Busan buildings, the X-axis decreased by 14%,

Table 4 Weibull parameter and wind direction frequency

Daegu				Busan			
W.D.	A_i (%)	c_i	k_i	W.D.	A_i (%)	c_i	k_i
N	0.1	6.3	12.1	N	7.4	9.3	4.5
NNE	0.2	5.1	3.1	NNE	13.5	7.9	3.6
NE	0.6	5.4	3.1	NE	9.9	7.2	4.8
ENE	0.9	5.9	3	ENE	0.7	6.2	4.8
E	13.9	7.3	5	E	1.2	6	5.5
ESE	11.3	6.8	3.5	ESE	2.8	5.9	5.2
SE	11.9	6.5	4.1	SE	3	5.9	4.7
SSE	2.0	6.2	3.7	SSE	0.7	10.4	2.1
S	0.7	5.8	6.7	S	8.2	8	4
SSW	0.1	5.8	20	SSW	10.3	9.3	3.5
SW	0.5	5.7	2.9	SW	9.9	12.3	3.9
WSW	3.9	6.2	3	WSW	5.5	10.3	4
W	28.2	6.6	3.2	W	8.4	9.9	4.2
WNW	20.0	7.6	3.5	WNW	4.4	9.6	4
NW	5.1	6.7	3.5	NW	1.6	7.7	6.2
NNW	0.5	5.8	3.4	NNW	12.4	8.8	4.9

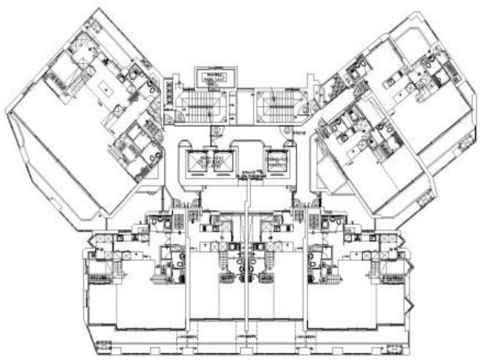
(a)



(b)

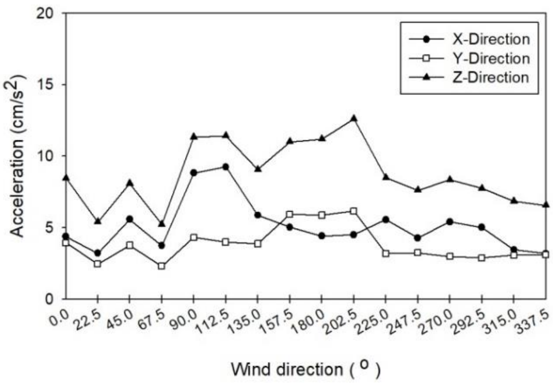
Fig. 4 surface roughness around of the example building

(a)

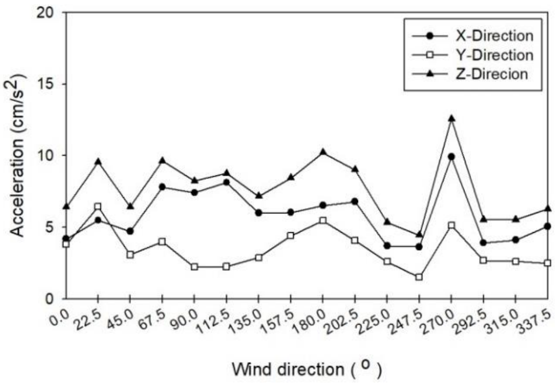


(b)

Fig. 5 Plan of the example building

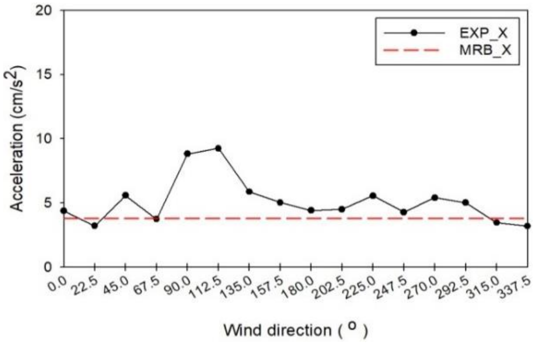


(a) Daegu's building

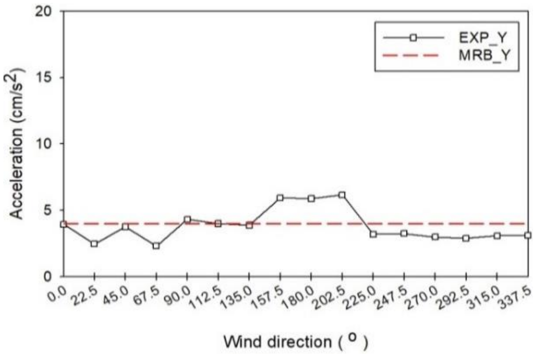


(b) Busan's building

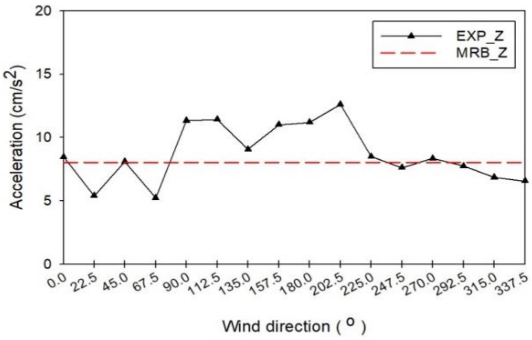
Fig. 6 Response acceleration by wind direction



(a) X-direction



(b) Y-direction



(c) Z-direction

Fig. 7 Comparison of response acceleration and MRB by wind direction in Daegu's building

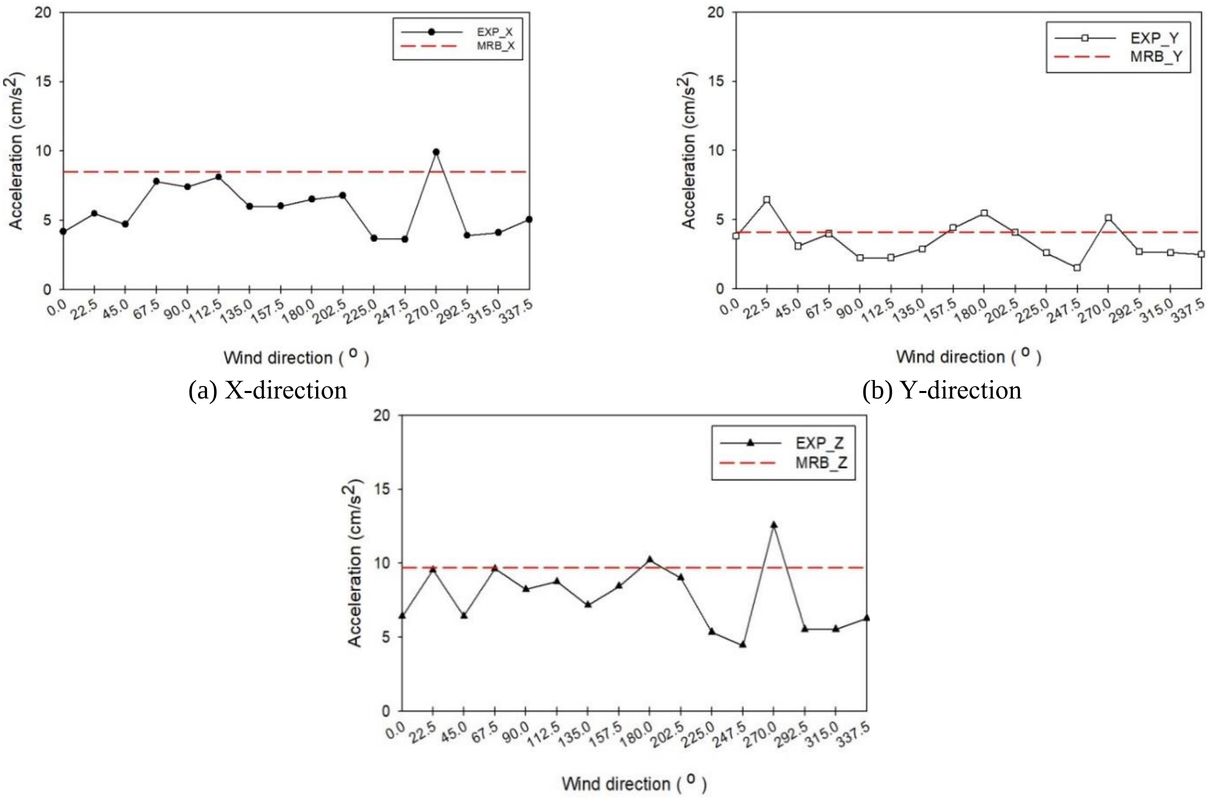
Table 5 (a) Dynamic characteristics of Daegu's building

Dynamic characteristics	X-Direction	Y-Direction	Z-Direction
Natural frequency (Hz)	0.1835	0.2251	0.1568
Generalized mass (ton)	9,234	9,663	
Generalized mass moment of inertia (ton·m^2)			1,308,050
Damping	0.009	0.009	0.009

Table 5 (b) Dynamic characteristics of Busan's building

Dynamic characteristics	X-Direction	Y-Direction	Z-Direction
Natural frequency (Hz)	0.276	0.328	0.406
Generalized mass (ton)	20,368	21,756	
Generalized mass moment of inertia (ton·m^2)			3,870,414
Damping	0.009	0.009	0.009

the Y-axis decreased by 36% and Z-axis decreased by 23%, as compared to the maximum response acceleration calculated by the same wind speed. In addition, it can be seen that one response acceleration is calculated for each structural axis because the method considers all of the excess probability of the wind speed according to the



(a) X-direction (b) Y-direction

(c) Z-direction

Fig. 8 Comparison of response acceleration and MRB by wind direction in Busan's building

response of each building's wind direction. The Busan buildings decreased less than the Daegu buildings using the MRB method. This is because the Weibull parameters include local wind speed characteristics. In other words, the wind speed in Busan area is stronger than that in Daegu area, so the decrease is less even considering the wind direction.

3.2 Method by estimation of wind speed by wind direction (MWD)

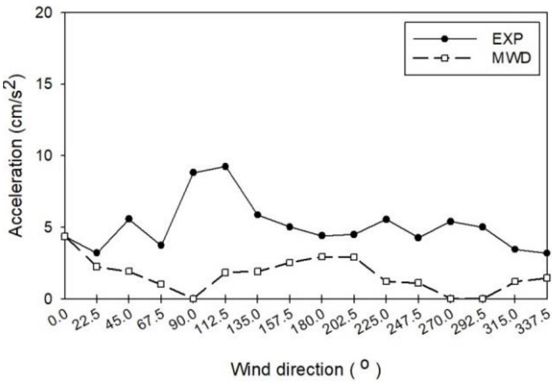
To perform serviceability evaluation through the MWD method, the 1-year return-period wind speed was calculated for each wind direction in Daegu and Busan and is shown in Table 6.

As shown in Table 4, the wind direction with a high wind directional frequency produced a large wind speed, and Busan showed high wind speed values, overall. In addition, wind speeds were not calculated because of the very low frequencies of the wind in the N, NNE, and SSW-directions in Daegu.

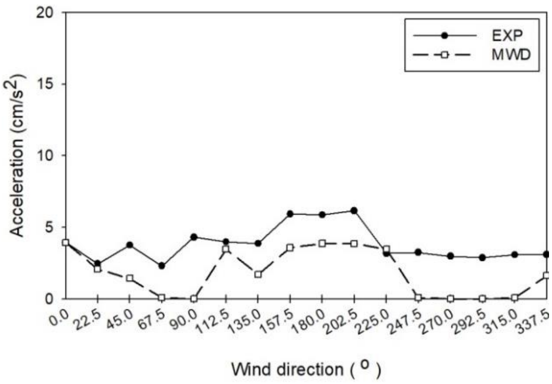
Figs. 9 and 10 is a comparison graph of the response acceleration calculated using the 1-year return-period wind speed for each wind direction, shown in Table 6 and the response acceleration rate that performed the wind tunnel test at the same wind speed for all wind directions. Compared to the maximum response acceleration, In Daegu buildings, the X-axis decreased by 53%, the Y-axis decreased by 37%, the Z-axis decreased by 36%, and in the Busan case, the X-axis decreased by 16% and the Y axis decreased by 32%, the Z-axis decreased by 22%. In addition, the response acceleration tended to differ from that obtained using a conventional analysis. For example, a particular wind direction produced the lowest response acceleration through the previous analysis, but the analysis through MWD shows that the highest response acceleration occurs. As explained in the MRB, the Weibull parameter

Table 6 1-year return period wind speed by wind direction

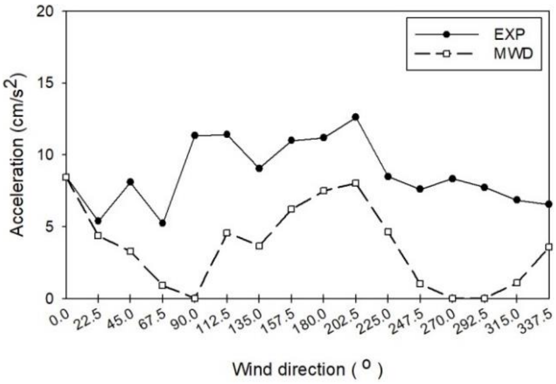
W.D.	Daegu (m/s)	Busan (m/s)
N	-	12.18
NNE	-	11.53
NE	5.01	9.45
ENE	6.23	6.17
E	9.65	6.47
ESE	9.87	6.94
SE	8.99	7.17
SSE	7.50	9.74
S	5.71	10.84
SSW	-	13.45
SW	5.03	17.16
WSW	8.54	13.64
W	10.74	13.28
WNW	11.50	12.46
NW	9.09	8.43
NNW	4.85	11.49



(a) X-direction

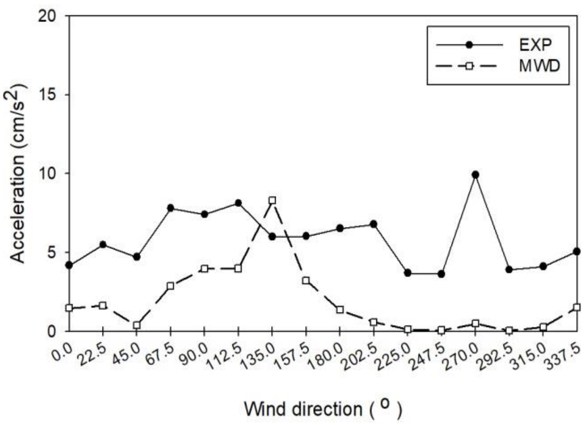


(b) Y-direction

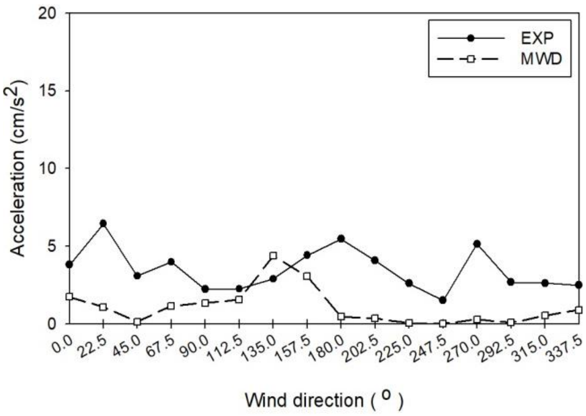


(c) Z-direction

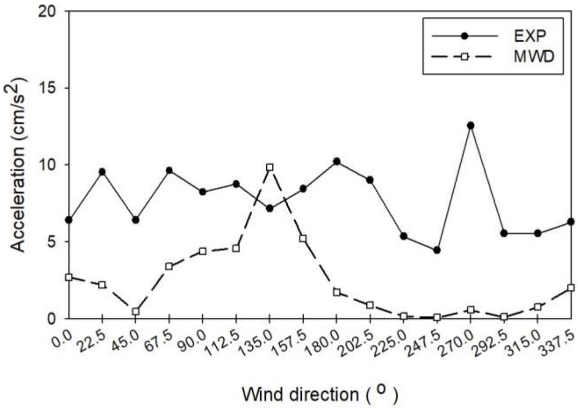
Fig. 9 Comparison of response acceleration and MWD by wind direction in Daegu's building



(a) X-direction

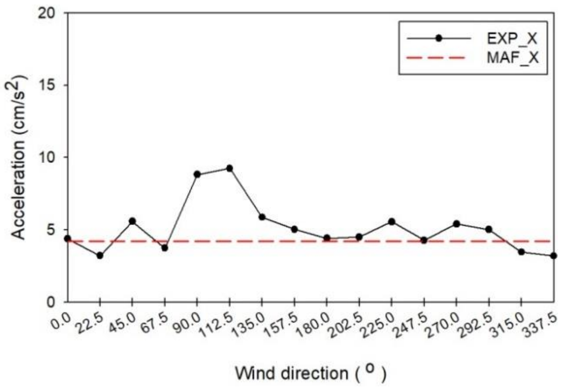


(b) Y-direction

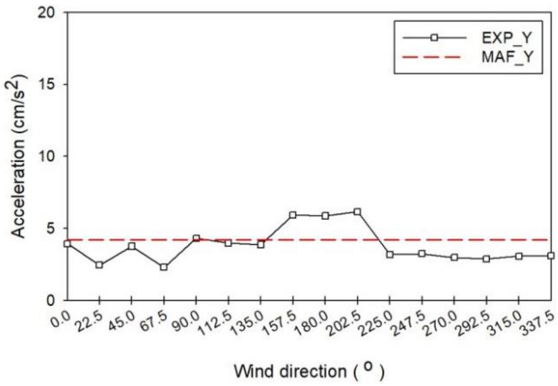


(c) Z-direction

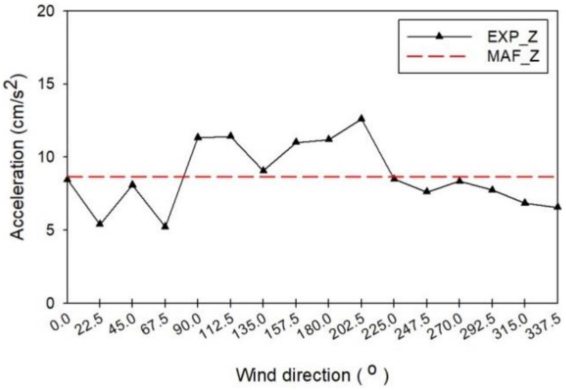
Fig. 10 Comparison of response acceleration and MWD by wind direction in Busan's building



(a) X-direction



(b) Y-direction



(c) Z-direction

Fig. 11 Comparison of response acceleration and MAF by wind direction in Daegu's building

contains wind speed characteristics, which means that Daegu has a much lower response speed than Busan. However, the MWD method calculates the 1-year return-period wind speed for each wind direction through a probability distribution combining wind speed and frequency. For this reason, it can be said that the Daegu building is properly arranged with the strong axis of the building and the strong wind direction.

3.3 Method by acceleration and wind directional frequency (MAF)

The serviceability evaluation of the target building was performed through the MAF method, and the response accelerations calculated with the same wind speed in the wind direction and the 1-year return-period response acceleration calculated using the MAF method were compared in Figs. 11 and 12.

For the Daegu buildings, the X-axis decreased by 55%, the Y-axis decreased by 32% and the Z-axis decreased by 31%, while the Busan building X-axis decreased by 42%, the Y-axis decreased by 44% and Z-axis decreased by 38%, as compared to the maximum response acceleration calculated by the existing assumptions.

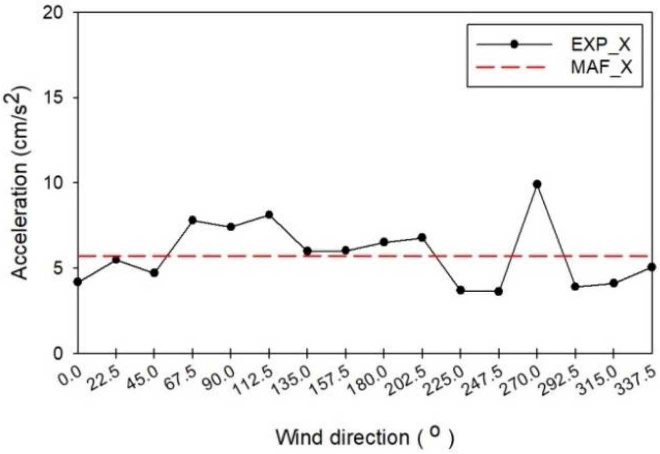
Unlike the MRB method and the MWD method, there is no significant difference in the response reduction rate of buildings according to the area. The reason is that the MWD method reduces acceleration by using only the frequency, not the combined distribution of wind speed and frequency. Therefore, the response acceleration can be effectively lowered only by the strong axis of the building and the arrangement of the wind direction of the strong wind speed, and the response acceleration is calculated by multiplying the response acceleration and the frequency of all the wind directions, so that one response acceleration is calculated as in Figs. 11 and 12.

3.4 Comparison and consideration of serviceability evaluation methods

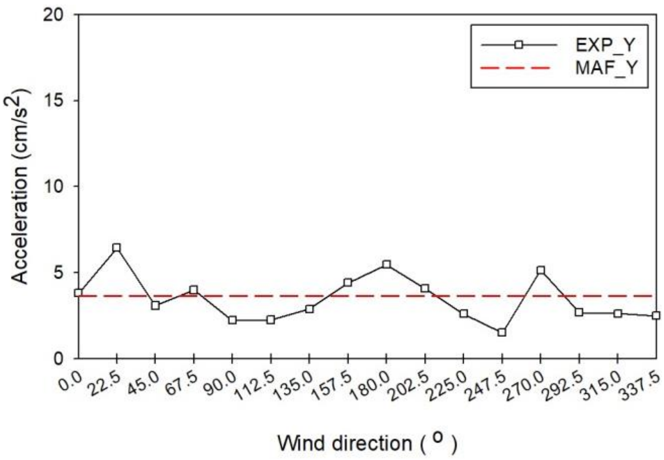
Table 7 compares the response acceleration, calculated using the serviceability evaluation method based on the wind directional frequency in this study.

Table 7 Comparison of existing methods and the methods of this paper

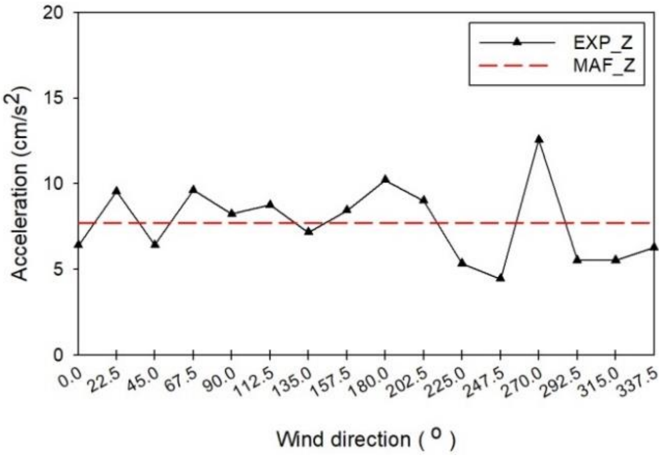
Analysis method	Daegu			Busan		
	Acceleration (cm/s^2)			Acceleration (cm/s^2)		
	X-dir	Y-dir	Z-dir	X-dir	Y-dir	Z-dir
EXP	9.25	6.15	12.6	9.91	6.45	12.55
MRB	3.80	4.00	8.00	8.50	4.10	9.70
MWD	4.36	3.92	8.45	8.28	4.37	9.83
MAF	4.20	4.20	8.67	5.72	3.63	7.71
	Reduction ratio (%)			Reduction ratio (%)		
MRB	58.9	35.0	36.51	14.2	36.4	22.71
MWD	52.9	36.3	32.94	16.4	32.2	21.67
MAF	54.6	31.7	31.19	42.3	43.7	38.57
Average	55.5	34.3	33.54	24.3	37.5	27.65



(a) X-direction



(b) Y-direction



(c) Z-direction

Fig. 12 Comparison of response acceleration and MAF by wind direction in Busan's building

The maximum value of the response acceleration calculated from the existing assumptions and the response acceleration from three methods were compared. All three methods reduce the response acceleration compared to the existing method and present one response acceleration as the 1-year return-period response acceleration.

Although the maximum values of the response acceleration for buildings in Daegu and Busan obtained through the wind tunnel tests are similar to each other, the calculated 1-year return-period response acceleration shows that Busan exhibits a lower overall decline. This is because the MRB method and the MWD method depend on Weibull parameter. The Weibull parameter reflects the characteristics of the wind in the target site because it is estimated through wind speed on the target site. Therefore, the decrease rate of the response acceleration calculated using the Weibull parameter for the building in Busan, which is usually subject to high-speed winds, is low. In addition to the Weibull parameter, the values can vary through the placement of the building's weak axis, rigid axis, and high wind directional frequency. The response acceleration can also be reduced through the arrangement of the flat surface roughness and through a low wind directional frequency. Unlike the other two methods, the MAF method has a low reduction rate, even in Busan, because the MAF method uses only the wind directional frequency and the response acceleration without the Weibull parameter. Therefore, the response acceleration can be easily reduced by simply arranging the strong axis and wind directional frequency, without depending on the local characteristics.

4. Conclusions

In this study, three serviceability evaluation methods considering wind directional frequency are presented for reasonable serviceability evaluation.

- The serviceability evaluation method considering wind directional frequency suggests that the acceleration of the 1-year return-period response acceleration is different from that of the conventional serviceability evaluation method.
- All three serviceability evaluation methods have lower response accelerations than the conventional method because of the consideration of the wind directional frequency.
- For Daegu buildings, the X-axis shows a decrease rate of 55% on average, the Y-axis shows a 34% decrease rate,

the Z-axis shows a 33% decrease rate, and the Busan building shows a decrease rate of 24% on the X-axis, 37% on the Y-axis and 27% on the Z-axis. Because of the Weibull parameter, which reflects the characteristics of wind speed, Busan with a higher basic wind speed showed a lower reduction rate.

• “Method by estimation of wind speed by wind direction” (MRB) is highly reliable because it uses dynamic characteristics as well as the wind directional frequency. However, since the return period corresponding to the response acceleration level is estimated and the wind speed must be calculated, there exists uncertainty and difficulty.

• “Method by estimation of wind speed by wind direction” (MWD) has a high reliability because it calculates and estimates the 1-year return-period wind speed according to the wind direction, but it requires much time because each wind direction must be analyzed through different laws of dynamical similarity.

• “Method by acceleration and wind directional frequency” (MAF), unlike other methods, is not significantly affected by regional characteristics, as it uses only the wind direction frequency without the Weibull parameter.

In addition, since the response acceleration can be lowered only by arranging the strong axis and the wind direction, it can be easily applied to the conventional wind tunnel test method.

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