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A Study on the Characteristics of the Evaluation Methods for Wind-induced Responses and Forces

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Abstract

Generally, the high frequency force balance test and the pressure test are widely used for the practical evaluation of wind-induced fluctuating responses and forces. Occasionally, the aero-elastic model test is taken for the assessment of responses to consider the interaction between a structure and wind flow. Also, the transient dynamic analysis using concurrently measured pressure data is utilized to examine the more realistic responses of structures. However, the evaluation results of each method seem to show a little difference on account of the inherited limitations or the assumptions in applications. Therefore, the characteristics of those methods are needed to be investigated for proper applications in practical works. In this study, the peculiar features of each method were summarized, and the analysis results of wind tunnel tests were compared to derive the distinctions of the evaluation methods.

Keywords: force valance test, pressure test, aero-elastic test, transient dynamic analysis

1. Introduction

The force balance test has been used as the most practical method to assess wind-induced forces and responses of tall buildings. The force balance test is performed on the assumption that the 1st vibration mode governs the total dynamic behaviors. Also, the generalized forces for the dynamic analysis are determined with the linear mode vector because wind forces along the heights of a structure cannot be measured.

Nowadays, concurrently measured pressure data at multiple points over an entire structure can be used for the analysis of wind-induced structural responses. The generalized forces can be derived with pressure data along the heights of a structure and the profile of wind forces could be obtained directly from tests. However, the evaluation results with the pressure test might be distorted according to the inappropriate pressure point locations. Also, the results of spectral reponse analysis with pressure data generally consider only the 1st vibration mode effect

The aero-elastic model test is occasionally used for the more exact evaluation of fluctuating responses in case of slender structures because the aero-elastic test model can consider the additional wind force caused by the interaction between a structure and wind flow. However, it takes lots of time and efforts to make an aero–elastic model. Hence the rocking model test designed to represent only the 1st vibration mode is usually used to assess the responses of slender structures for practical purpose.

Also, the transient dynamic analysis using pressure data acquired in the pressure test is performed to investigate the more realistic behaviors of structures. In most cases, the structure system of residential buildings in Korea is composed of cores and shear walls with asymmetric planar plan. Generally, the dynamic behaviors of such a building are quite complex, therefore it might be irrelevant to evaluate the dynamic responses through a simplified approach such as the force balance test. The dynamic responses of such buildings could be accurately calculated through the transient analysis using pressure data acquired through wind tunnel tests.

Above the four types of evaluation methods could be applied in engineering works for practical purposes. However, the characteristics of each method are needed to be clarified for appropriate applications with increase of the extraordinary shapes of structures.

In this study, the specific features of above evaluation methods were analyzed with the examples of rectangular shape structures. Firstly, the properties of local pressures were investigated to determine the proper locations of pressure points for the derivation of more accurate wind forces. And then, the base shear

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Fig. 1. Wind tunnel test

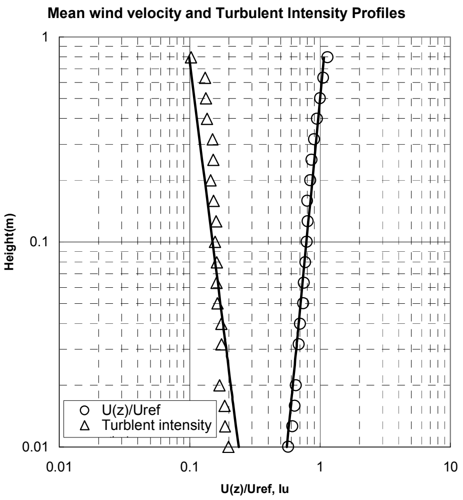


Fig. 2. Mean wind velocity and turbulent intensity

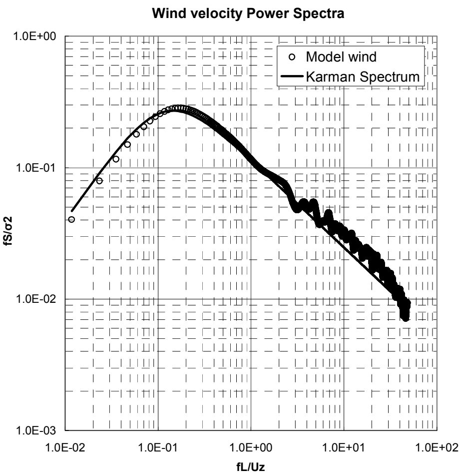


Fig. 3. Wind velocity power spectra

and the base moment spectrums derived through the force balance test and the pressure test were compared to investigate the pertinence of the pressure test for the evaluation of wind forces. Additionally, the rocking model test and the transient dynamic analysis using pressure data were performed, and the responses of the evaluation methods were compared with each other to clarify the characteristics of each method.

Table 1. Types of wind tunnel tests

Model	Type of Test	Dimension(mm)
SR4P1	Pressure Test	75(B)×75(D)×300(H)
SR4P2	Pressure Test	75(B)×75(D)×300(H)
SR4F	Force Balance Test	75(B)×75(D)×300(H)
SR12P	Pressure Test	34(B)×34(D)×400(H)
SR12F	Force Balance Test	34(B)×34(D)×400(H)
SR12A	Aero-elastic Test	34(B)×34(D)×400(H)

2. Wind tunnel test

Several wind tunnel tests were carried out to analyze the special features of the evaluation methods. The types of the test models are summarized in Table 1. The slenderness ratios of SR4 and SR12 types were 4 and 11.7, respectively. The SR4P1 model was designed to observe the local pressure properties and the SR4P2 and the SR12P were designed to derive overall wind forces acting on the models. The SR4F and the SR12F were the force balance test models, and The SR12A was the rocking vibration model.

The wind tunnel experiments were performed in the wind tunnel laboratory of DAEWOO Institute of Construction Technology as shown in Fig.1. The model wind was flow over the open terrain area of which the power-law exponent α was 0.15. The mean wind velocity and turbulent intensity profiles used for the tests are depicted in Fig. 2. Also, the wind velocity spectrum of the model wind is shown in Fig. 3 together with the Karman spectrum.

The test data were sampled at the rate of 400Hz for about 80 seconds. The force data were filtered at 100Hz with low-pass analogue filters and the pressure data were digitally filtered at the cutoff frequency 100Hz. All pressures were measured simultaneously and the measured pressure data were digitally compensated for the tube response due to resonance, damping and phase lag.

3. Local pressure properties

The pressure properties of local areas were analyzed along the horizontal line of the SR4P1 model to investigate the proper locations of pressure points for the appropriate wind force assessment as shown in Fig. 4. The measured pressures were expressed as coefficients referenced to the pressure at the height of the top of the test model. Also, the location of each pressure point on the model was normalized with the width B of the test model.

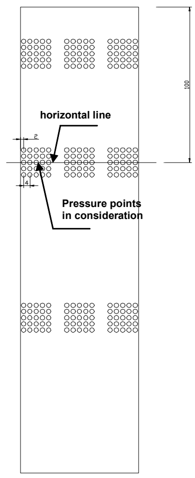
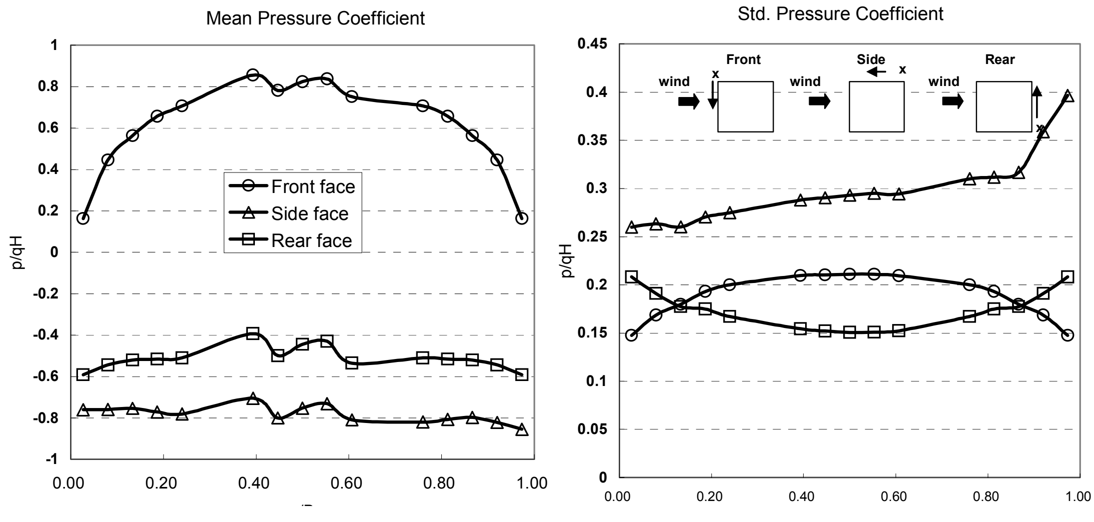


Fig. 4. Local pressure Model (SR4P1)

The mean pressure coefficients of the front face within about 20% of the model width around the edges are observed to show varying rapidly in Fig. 5 (a).



(a) mean Cp (b) rms Cp

Fig. 5. Local pressure distributions

The mean pressures around the edge of the side and rear face show approximately uniform distributions without radical changes. The pressures around center of the model are observed to randomly fluctuate, however those seem to have an arbitrary mean value.

The rms pressures depicted in Fig. 5 (b) also show the tendency of variations near the edge of the model. Especially, the rms pressures of the side face within about 10% of the model width around edge where the separation occurs are observed to change rapidly. The rms pressures of the side face tend to decrease from the separation edge to the opposite. The rms pressures of the front and rear side around the center of the model also seem to have an average value.

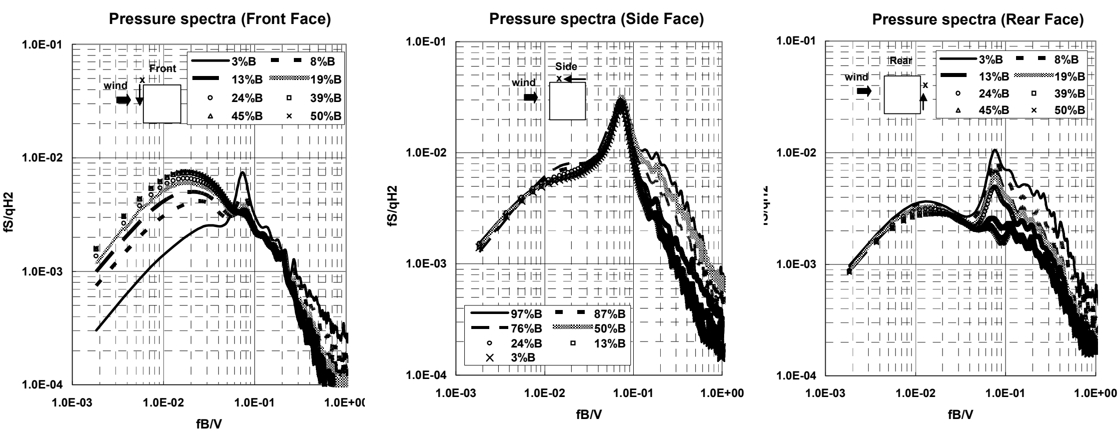
The results of the pressure spectra are depicted in Fig. 6. The pressure spectra of the front and the rear face around edge within about 20% of the model width show the peak value at the Strouhal number. Also, the high frequency regions of pressure spectra around the edge of the rear face seem to have more energy than those around the center of the face. The pressure spectra of the side face are observed to have the peak at the Strouhal number, but the energy of the high frequency regions around the edge part where the separation takes place is higher than the other parts.

The pressures along the heights of the model were observed to show similar properties in pressure distributions and spectra described previously except around the top of the model.

Hence, it could be concluded that a guide on the pressure point plan is required to obtain more accurate wind forces with the pressure test. In this study, it was tentatively determined as follows:

(i) At least, a pressure point must be installed within 20% of the model width to detect the variation of pressures along the width of models and the separation effects observed in the power spectra.

(ii) At least 3 pressure points around the center of a face within 60% of the model width should be installed uniformly to identify the statistical trend of pressures and the spectra variation.



(a) Front face (along wind) (b) Side face (across wind) (c) Rear face (along wind)

Fig. 6. Power spectra of local pressures

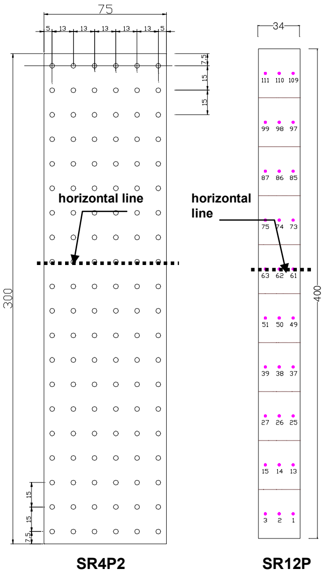
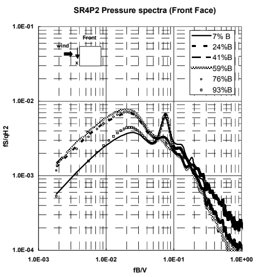
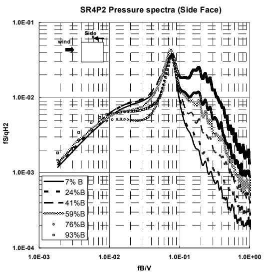


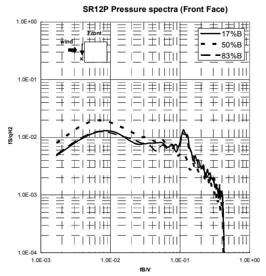
Fig.7. SR4P2 & SR12P Models



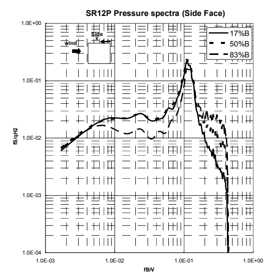
(a) SR4P2 (Front face)



(b) SR4P2 (Side face)



(c) SR12P (Front face)



(d) SR12P (Side face)

Fig. 8. Pressure spectra along the horizontal line

4. Comparison of force spectra

The force spectra derived with the pressure test and the force balance test were compared to investigate the pertinence of pressure data for the evaluation of wind forces. The test models are shown in Fig. 7. The pressure test and the force balance test were performed for SR4P2/SR12P and SR4F/SR12F, respectively. The numbers of pressure points of SR4P2 and SR12P were 120 points and 30 points on each face, respectively. A pressure point was installed on each edge surface within about 20% of the model width and 4 pressure points were installed around the center part of a surface for the SR4P2 model. In case of the SR12P model, a pressure point was installed on each edge surface and each center surface, respectively. As the width of the SR12P model was narrow, a pressure point was expected to be enough to measure the pressures on the center part of the surface.

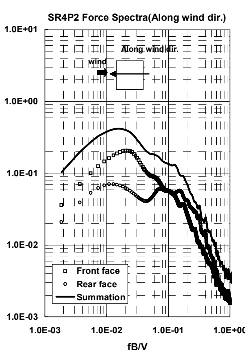
At first, the power spectra of pressures along the horizontal line of each model were derived as shown in Fig.7, and the results are presented in Fig. 8. The pressure spectra show that each point was reasonably located to measure the fluctuating pressure properties around the edge and the center of a surface. The separation effect is well represented in the pressure spectra of edge parts and the overall shapes of the spectra observed in the test of SR4P1 also can be seen in those of the SR4P2 and SR12P model.

The force spectra acting along the horizontal line of each model are depicted in Fig. 9. The forces were calculated by integrating pressure data with tributary areas as described in Eq. (1).

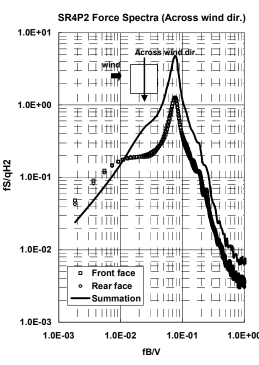
$$F(t) = A_{\max} \sum_{i=1}^{n} P_i(t) \frac{A_i}{A_{\max}} \quad (1)$$

where, n is the number of pressure points, A_i is tributary area for the pressure point at location i, $A_{\max}$ is the maximum tributary area, and $P_i(t)$ is pressure of the pressure point i.

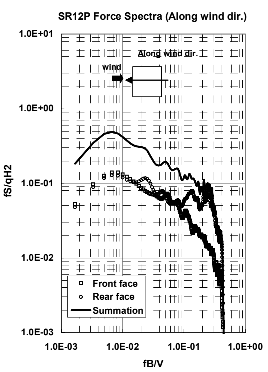
The peak at the Strouhal number appeared in the pressure spectra of the edge points are disappeared in the force spectra of the along-wind direction through



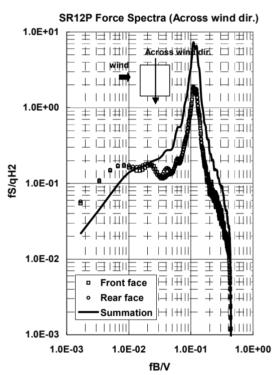
(a) SR4P2 (along wind)



(b) SR4P2 (across wind)

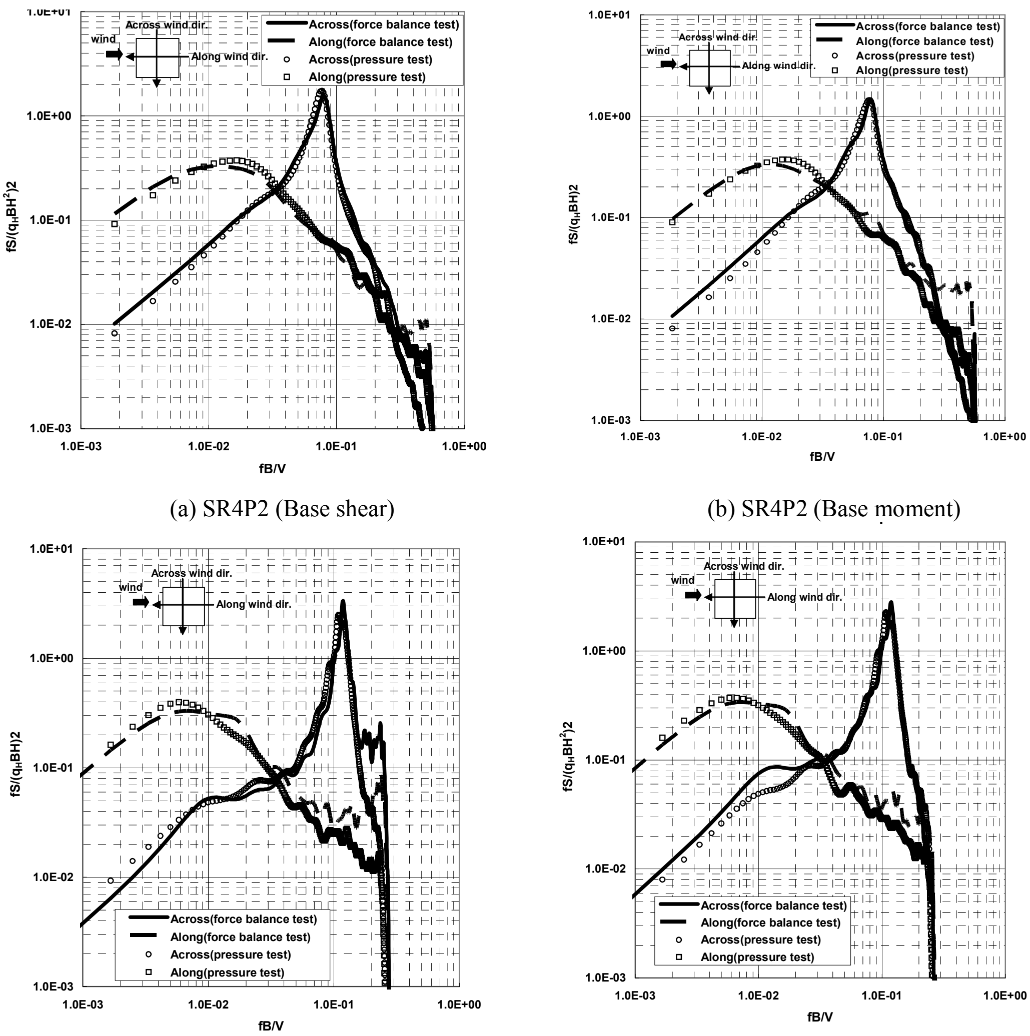


(c) SR12P (along wind)



(d) SR12P (across wind)

Fig. 9. Force spectra along the horizontal line



(a) SR4P2 (Base shear) (b) SR4P2 (Base moment)

(c) SR12P (Base shear) (d) SR12P (Base moment)

Fig. 10. Base shear and base moment spectra

the integration of pressures, while the peak still exists in the force spectra of the across-wind direction as shown in Fig. 9. It could be inferred from the force spectra that the correlations of the pressure fluctuations at the Strouhal number for the along wind direction are much less than those for the across-wind direction. As a consequence, the effect of the separation was disappeared for the along wind direction while such effect become clearer for the across wind direction.

The base shear and the base moment spectra derived with the pressure test and the force balance test were compared as depicted Fig. 10. The base shear was assessed by integrating all pressures acting on entire surface using Eq. (1). The base moment was calculated by integrating pressures multiplied by moment arms with tributary areas as following equation.

$$M(t) = A_{\max} \sum_{i=1}^{n} P_i(t)\, h_i \frac{A_i}{A_{\max}} \tag{1}$$

Where h_i is a moment arm from the base at location i. It can be seen that the base shear and the base moment spectra derived from pressure data are in a good agreement with those derived from force data in Fig. 10. The force coefficients are listed in Table. 2.

Table 2. Force coefficients (x : along wind, y : across wind)

Coefficients	SR4P2		SR12P	
	Force Test	Pressure Test	Force Test	Pressure Test
CFx(mean)	1.05	1.08	1.22	1.26
CFx(rms)	0.23	0.24	0.24	0.25
CFy(rms)	0.34	0.34	0.33	0.34
CMx(mean)	0.55	0.55	0.90	0.92
CMx(rms)	0.13	0.12	0.13	0.14
CMy(rms)	0.17	0.17	0.17	0.18

5. Rocking model test

The rocking model test was taken to investigate the effect of the interaction between a structure and wind flow to the dynamic responses. An arbitrary structure was developed to evaluate responses for the SR12A test model. The length scale of the test model to the full scale structure was 1/250 and the model wind velocity scale to the design wind velocity was 1/6.

The SR12A model was installed on the rocking model test apparatus as shown in Fig. 11. The dynamic properties of the full scale structure were modeled in the test model as shown in Fig. 12 according to the

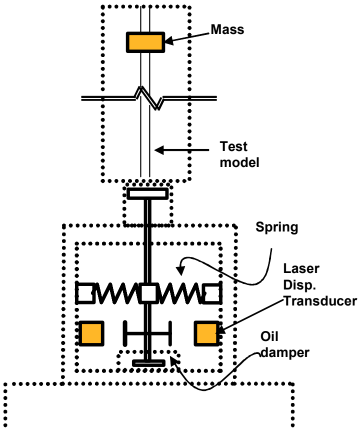


Fig. 11. Rocking model test apparatus

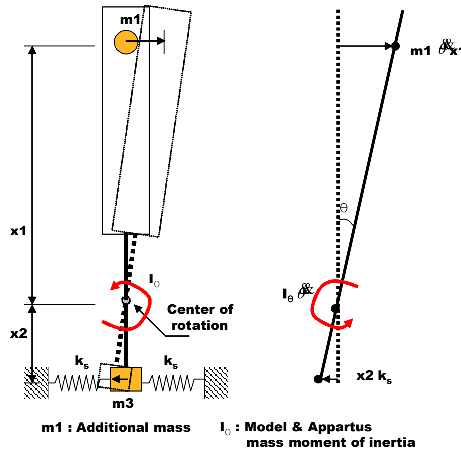


Fig. 12. Assignment of dynamic properties

similarity ratios. The dynamic properties were derived through the modal analysis of the full scale structure. The dynamic properties and the geometric dimensions of the full scale structure and the test model are summarized in Table 3.

The displacement response data were sampled at the rate of 1000 Hz for about 50 seconds which were 35 minutes in full scale with laser displacement transducers. The measured data were digitally filtered at the cutoff frequency 100 Hz.

The trajectory of the displacement responses at the top of the structure is presented in Fig. 13 (a). The maximum displacements at the top of the structure were 0.18 m and 0.44 m for the along-wind and the across-wind direction, respectively. The maximum displacements were the ensemble-averaged values of 3 test samples.

Table 3. Dynamic properties and geometric dimensions

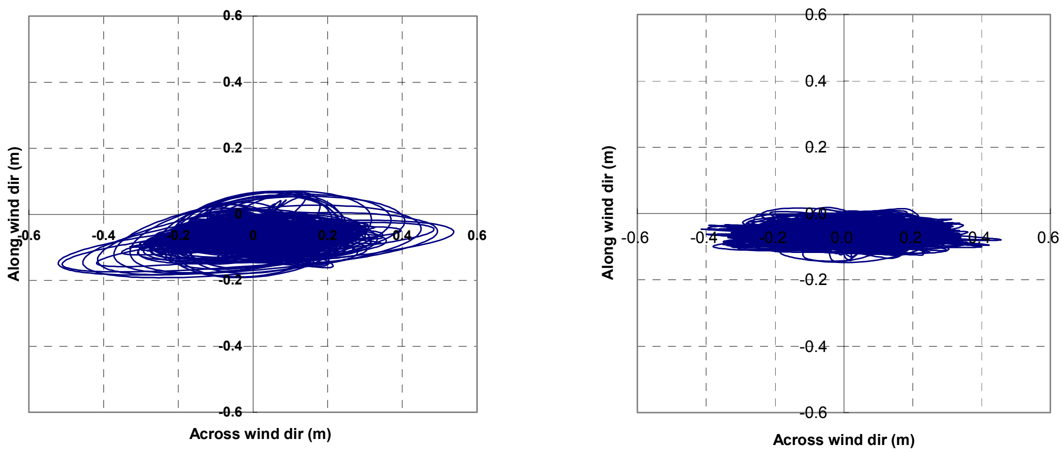
Coefficients	Full structure		SR12P model	
	x-dir	y-dir	x-dir	y-dir
H (m)	100		0.4	
B (m)	8.5	8.5	0.034	0.034
Natural frequency (Hz)	0.63	0.63	26.63	26.24
Rotational mass moment of inertia (kg cm^2)	1.10× 10^{14}	1.10× 10^{14}	113.8	112.8
Damping ratio	1.3%	1.3%	1.3%	1.35%

6. FEM transient dynamic analysis

The transient dynamic analysis using pressure data was performed to examine realistic structural behaviors to fluctuating wind pressures acting on the full scale structure developed for the rocking model test of SR12A. The time history pressure data were directly assigned to the tributary areas of the analysis model and the responses were calculated with the direct numerical integration method as shown in Fig. 14. The analysis was performed for about 10 minutes in full time scale. The maximum displacements at the top of the full scale structure were acquired from an analysis sample, which were 0.16 m and 0.43 m for the along-wind and the across-wind direction, respectively. The trajectory of displacements at the height of the top of the full scale structure is displayed in Fig. 13 (b)

7. Comparison of responses

The fluctuating responses of the developed full scale structures were also derived with the force balance test and the pressure test of the SR12 models. Those results



(a) Rocking model test result (b) FEM transient analysis results

Fig. 13. Trajectory of Displacement at the height of the top of the structure

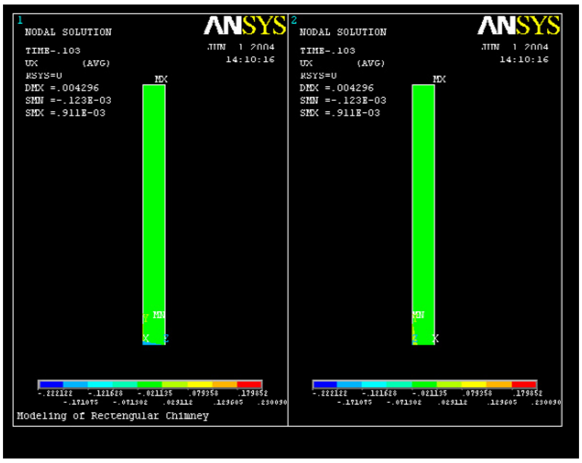


Fig. 14. FEM transient analysis

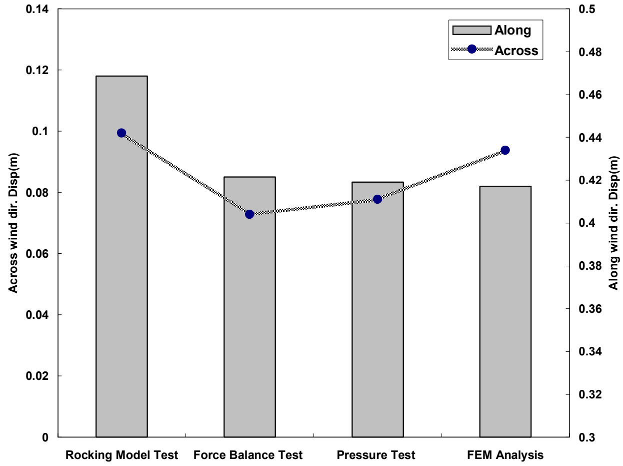


Fig. 15. Maximum fluctuating displacement

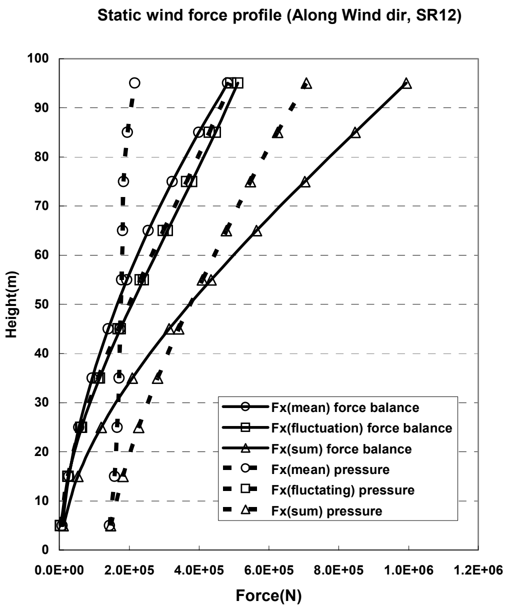
were compared with the responses assessed with the rocking model test and the transient dynamic analysis to investigate the properties of each response evaluation method.

In case of the response analysis using force balance test data, the base moment spectra are directly used as the generalized force spectra assuming that the 1st vibration mode of a structure is linear because forces can be measured only at the base of a model. Therefore, the responses assessed with the force balance test might include some errors. Hence, a modal correction is generally performed for reducing the errors included in the analysis results.

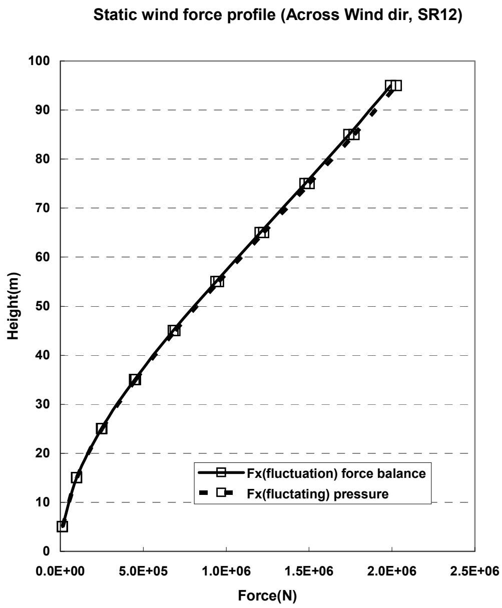
As for the pressure test, the generalized force spectra can be properly derived from the pressure data measured along the heights of a structure and the actual vibration mode shape. However, the higher vibration mode contributions couldn't be properly considered in the spectral response analysis of the pressure test results similar to that of the force balance test results.

The maximum displacements at the height of the top of the full scale structure assessed with each method are depicted in Fig. 15. The results of the rocking model test exhibit larger values than other methods, which imply that the effects of the interaction between the structure and wind flow increased the total responses.

The responses derived with the force balance test were adjusted through the modal correction method, and the results show a proper agreement with the results evaluated through the pressure test. Therefore, it is presumed that the dynamic responses could be properly evaluated with the force balance through the modal correction process for general buildings. The maximum response of the transient analysis for the



(a) Along wind direction



(b) Across wind direction

Fig. 16. Equivalent static wind loads

across-wind direction shows a tendency to be a little larger than those derived with the force balance test and the pressure test, which might be described by several reasons. At first, the contribution of higher vibration modes effects which couldn't be considered in the force balance and the pressure test analysis might increase the transient analysis responses. Also, the responses of the transient analysis might be increased because the peak responses could be directly analyzed by applying nonstationary negative pressures on the surface of the analysis model. Besides, the transient analysis results might not converge adequately to actual responses because of the insufficient number of samples

In sum, the aero-elastic test should be used for the evaluation of the interaction between a structure and wind flow for slender structures. The force balance test could derive proper dynamic responses through the modal correction process for general tall buildings. However, it might be desirable to apply the pressure test for the evaluation of the more accurate dynamic responses because the actual vibration mode shape and the actual pressure distribution can be considered. Besides, the effects of nonstationary negative pressures and higher vibration modes to total responses could be considered in the transient dynamic analysis through the direct application of pressure data on the analysis model and the numerical integration process.

8. Equivalent static wind loads

Generally, the equivalent static wind loads are evaluated for the practical structural design purpose. The static wind loads can be developed with the force balance test and the pressure test. The wind loads of the full scale structure for the SR12 model were derived and compared as shown Fig. 16. The fluctuating parts of the static wind loads derived with the force balance test for both of the along-wind and the across-wind direction exhibit a proper agreement with those derived with the pressure test. However, the mean wind profiles derived with both methods for along-wind direction show discrepancy in shape. The mean wind load profiles are commonly estimated according to a power-law in the analysis of the wind force test results because pressure or story forces couldn't be measured through tests. However, as shown in Fig. 16 (a), the mean wind profile derived with the force balance test based on the assumption of the power-law is considerably different with the actual profile measured in the pressure test. As a consequence, the total static wind loads derived with the force balance test and the pressure test for the along-wind direction shows a disagreement in profiles.

Therefore, the mean and the background part of wind loads need to be directly measured in tests for the derivation of more exact total static wind loads.

9. Conclusion

The characteristics of the response and wind load evaluation methods were investigated to obtain a guide for proper application in practical works.

The local pressure properties for a rectangular shape model were evaluated and the installation plan of pressure points could be tentatively suggested to acquire proper wind forces with the pressure test for this study. The comparison results of the base shear and the base moment spectra derived with the force balance test and the pressure test demonstrate that the wind forces could be adequately measured with the pressure test, provided that pressure points were properly located.

An arbitrary structure for the SR12 model was developed to compare the responses and the static wind loads derived with each evaluation method. As a result, the aero-elastic test should be taken to investigate additional increase in responses for slender structures. In most cases, the pressure test or the force balance test are expected to evaluate proper dynamic responses to fluctuating wind forces for general buildings, however the transient dynamic analysis seems to be required for the accurate evaluation of responses in case of extraordinary shapes of structures showing complex vibration properties and generating lots of nonstationary negative pressures.

Also, the equivalent static forces derived with the force balance test might be distorted because actual wind load profiles couldn't be measured in test. Therefore, it seem to be desirable that the mean and background fluctuation part of wind loads are measured directly in tests to obtain the proper total wind load profiles.

In future study, the organized plan of pressure point locations and the force measuring method through the pressure test will be comprehensively studied for practical structures. Also, the transient analysis will be enhanced to be conveniently used in practical engineering works.

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