Aerodynamic database for low-rise buildings

1. Introduction

An aerodynamic database has been constructed by the Tokyo Polytechnic University as one part of the Wind Effects on Buildings and Urban Environment, the 21st Century Center of Excellence Program, 2003-2007, funded by the Ministry of Education, Culture, Sports, Science and Technology, Japan. Present work is the low-rise building part of the aerodynamic database. Its objective is to provide structural design engineers with wind tunnel test data of wind loads on low-rise buildings. 116 models of gable-, hip- and flat-roofed low-rise buildings were tested. 4176 contours of statistical values of local wind pressure coefficients, 700 graphs of statistical values of area averaged wind pressure coefficients on the roof or wall surfaces and time series data of point wind pressure coefficients for 812 test cases are shown on this web site. These data can be used to calculate local wind pressures, area averaged wind pressure coefficient on roof or wall surfaces, and even wind induced dynamic responses of low-rise buildings.

The aerodynamic database of low-rise buildings can be queried from the lower part of this web page.

The following paragraphs provide information on wind tunnel tests, processes of obtaining test data, usage of the data.

2. Wind Tunnel Test

Pressure measurement wind tunnel tests on low-rise buildings for this database were executed in the Boundary Layer Wind Tunnel, 2.2m wide by 1.8m high, in the Tokyo Polytechnic University, Japan.

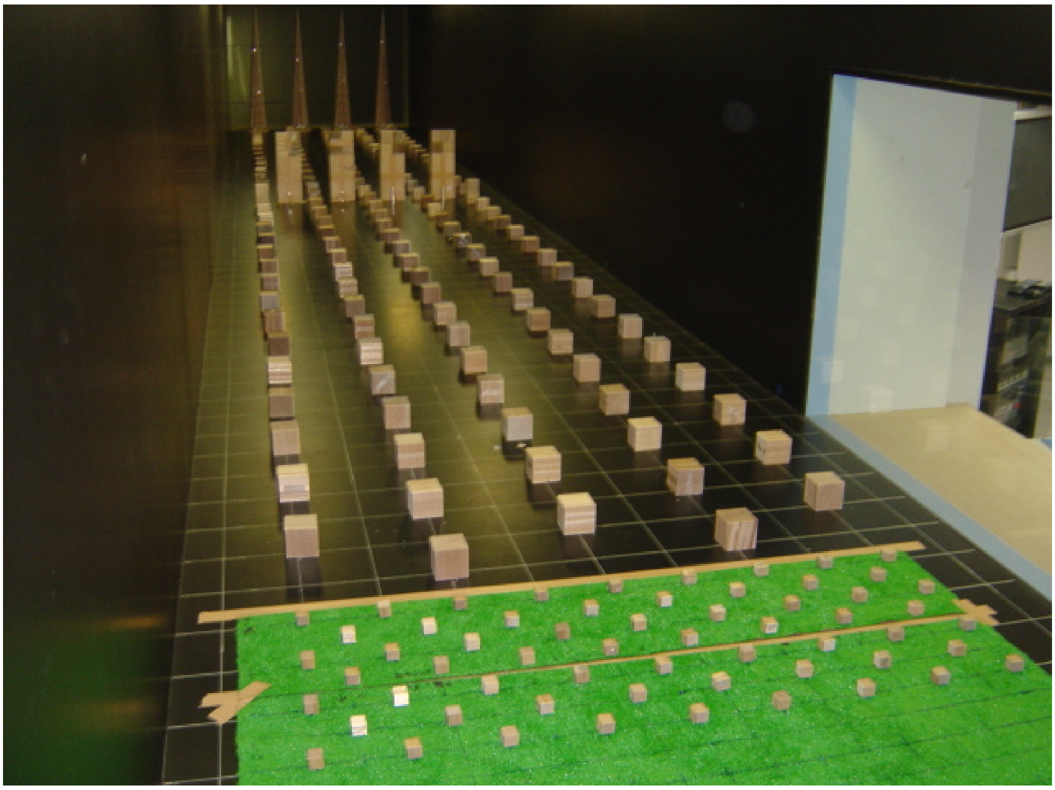
The length scale was set at 1/100. As the velocity scale was assumed at 1/3, the time scale can be estimated at 3/100.

2.1 Wind field

Since a lot of low-rise buildings are located in suburban areas in Japan and some other countries, the suburban terrain corresponding to terrain category III in AIJ (2004)[1] was chose as the tested wind field. This category has a mean wind velocity profile exponent of 0.20 and a gradient height of 450m. It was simulated with turbulence-generating spires, roughness elements and a carpet on the upstream floor of the wind tunnel's test section. The wind velocity profile and turbulence intensity profile of the simulated wind field are shown in Fig. 1. The turbulence density at a height of 10cm was about 0.25. The test wind velocity at this height was about 7.4m/s, corresponding to about 22m/s at a height of 10m in full scale.

2.2 Test models

To maximize the database's applicability, the geometric parameters of the tested models covered a wide range of combinations. Table 1 shows the geometric parameters of the 116 model cases of the



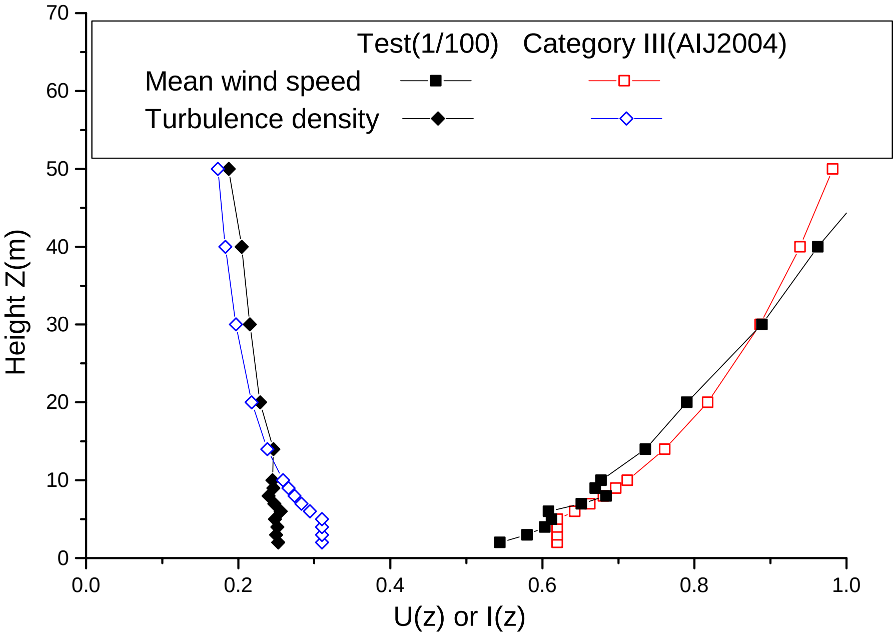


Figure 1. Simulated wind field of suburban terrain

wind tunnel test. Three types of models were tested: flat-roofed, gable-roofed and hip-roofed. Four Height/Breadth ratios were tested: 1/4, 2/4, 3/4 and 4/4. The Depth/Breadth ratios were set at 2/2, 3/2 and 5/2 for the flat- and gable-roofed models, and 3/2 for the hip-roofed models. For the gable-roofed models, 8 roof pitches were tested: 4.8^o, 9.4^o, 14^o, 18.4^o, 21.8^o, 26.7^o, 30^o and 45^o. 2 roof pitches were tested for the hip-roofed models: 26.7^o and 45^o. The pitches of the four slopes of a hipped roof were assumed same.

Table 1. Test model cases

Case number	Roof Type	*B*(mm)	*D*(mm)	*H0*(mm)	β (°)
1-12	Flat	160	160,240,400	40,80,120,160	0
13-44	Gable	160	160	40,80,120,160	4.8, 9.4, 14, 18.4, 21.8, 26.7, 30, 4.5
45-76	Gable	160	240	40,80,120,160	4.8, 9.4, 14, 18.4, 21.8, 26.7, 30, 4.5
77-108	Gable	160	400	40,80,120,160	4.8, 9.4, 14, 18.4, 21.8, 26.7, 30, 4.5
109-116	Hip	160	240	40,80,120,160	26.7, 45

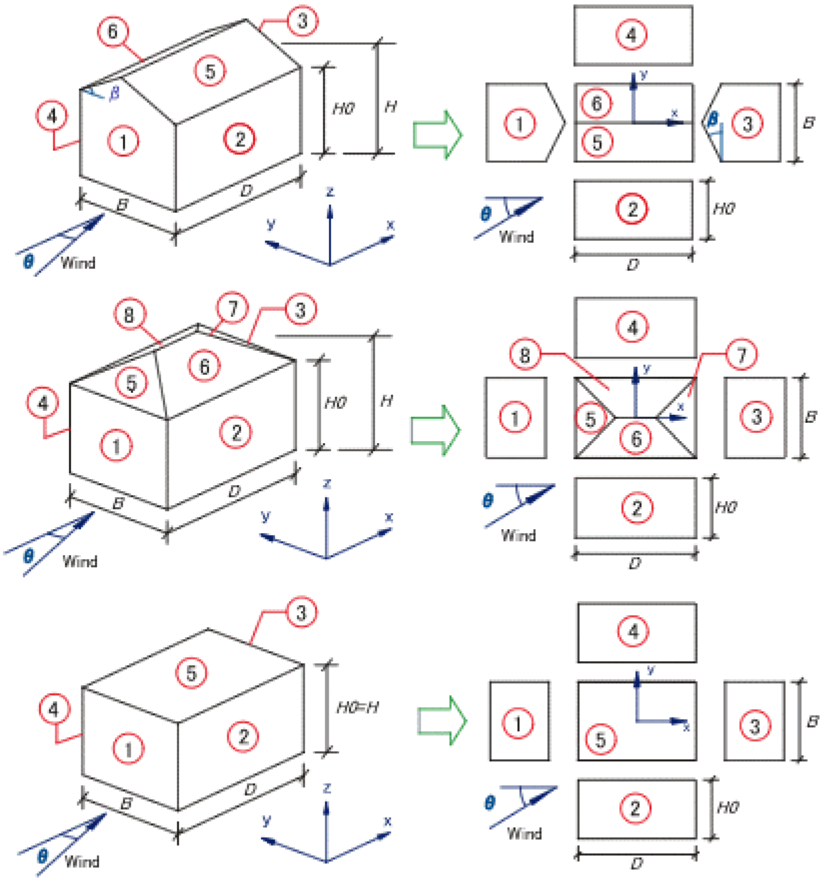
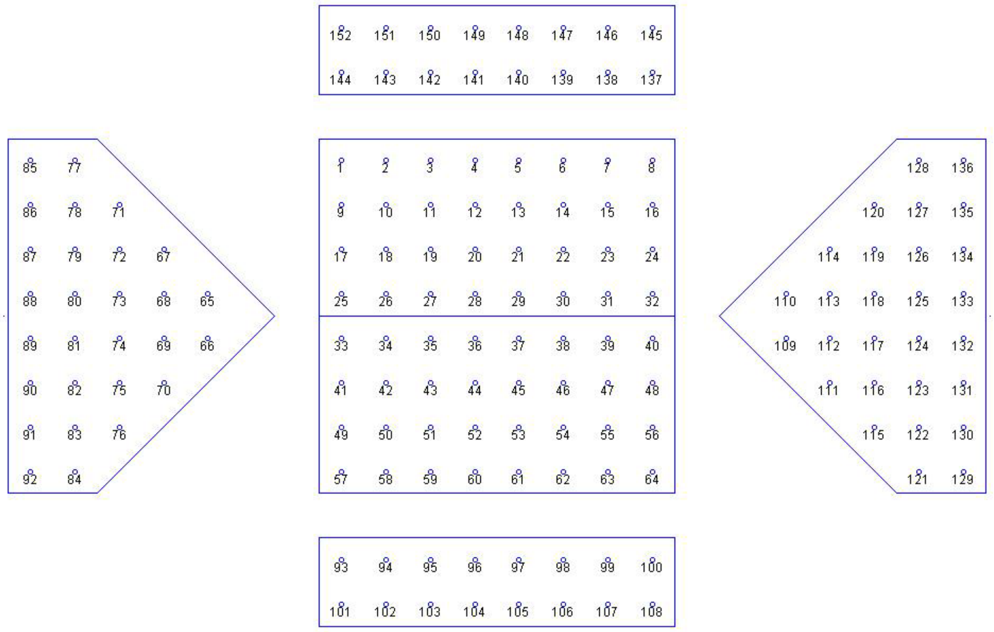


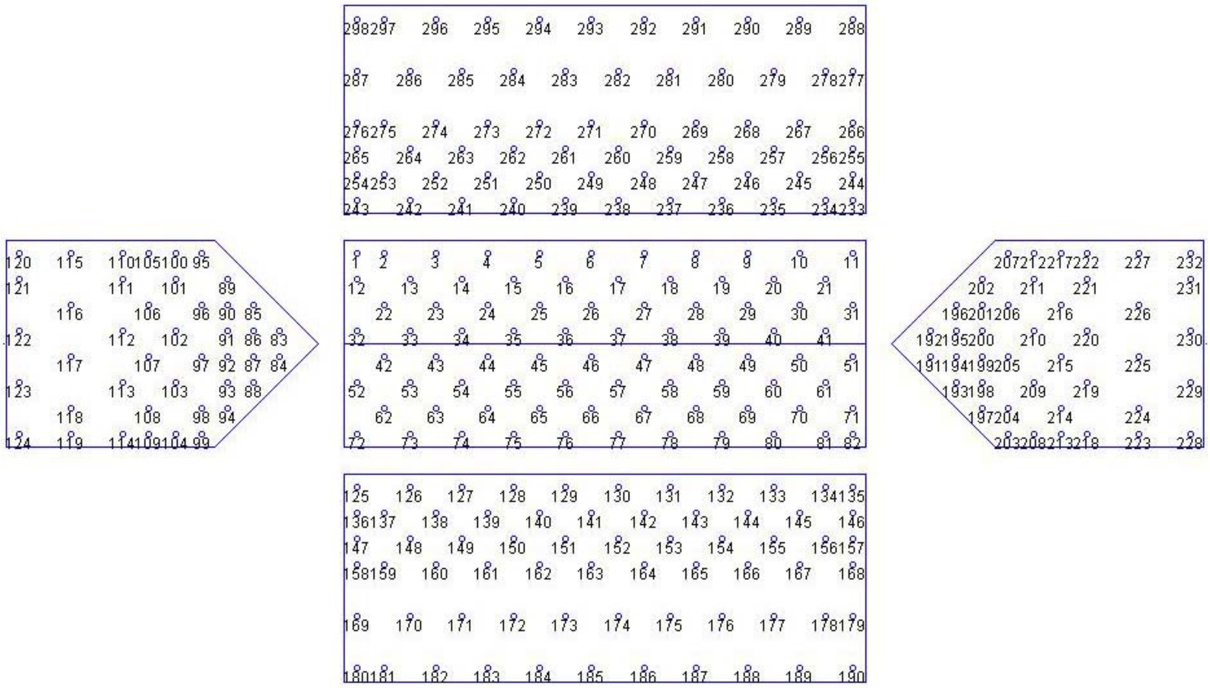
Figure 2. Test model and definitions of geometrical parameters and coordinates

Figure 2 shows test models of low-rise buildings. H0, B and D are eave height, breadth and depth of the building, respectively. H is mean roof height, which was set as the reference height of approach wind velocity for wind pressure coefficients. β is roof pitch. θ is wind direction angle, which was set at 0° when the wind direction was parallel to the ridge. The origin of the coordinates is located at the center of the roof and the x-axis is parallel to the ridge. The building surfaces are annotated by Arabic numerals. The four walls were set as Surface 1 ~ 4. The two slopes of a gable roof were set as Surface 5 and 6. The four slopes of a hipped roof were set as Surface 5 ~ 8. The whole roof of a flat-roofed building was set as Surface 5. For convenience, the contours of the local wind pressure coefficients were drawn with the five parts shown flat, as in the right part of Figure 2.



Position of measured points of a gable-roofed low-rise building

Building geometrical parameters: H=5.0m,B=16m,D=16m,β=45°



Position of measured points of a gable-roofed low-rise building
Building geometrical parameters: H=20.0m,B=16m,D=40m,β=45°

Figure 3. Arrangement of wind pressure measurement taps

2.3 Wind pressure measurement system

Wind pressure measurement taps were disposed uniformly over the surfaces of the tested models, as shown in Figure 3. Basic spaces among the taps were 20mm corresponding to 2m in full scale. Since the wind pressure measurement scanivalve couldn't measure a large number of taps synchronously, some inner points for models with larger surfaces were not measured. Synthetic resin tubes 80cm long and 1.2mm in internal diameter connected each tap with a pressure measurement scanivalve, which can measure the fluctuating wind pressures at 384 points nearly synchronously.

In this test, the sampling frequency was 500Hz and the sampling period was 18 seconds for each sample, corresponding to 15Hz and 10 minutes in full scale. Each test case was sampled 10 times.

3. Comparison with other test data

Levitan et al [2] studied the wind pressure coefficients on a full scale TTU model. Tieleman et al [3] and Luo [4] studied a model of a TTU test building at a scale of 1/50 in a wind tunnel at the University of Western Ontario (UWO) and at Tongji University (TJU), respectively. Holmes [5] also showed his test results in his textbook. In order to verify the validity of the present wind tunnel test data, mean wind pressure coefficients on the centerline of several gable roofs with similar test cases in the present test were compared with those in the literature [2-5] as shown in Figure 4.

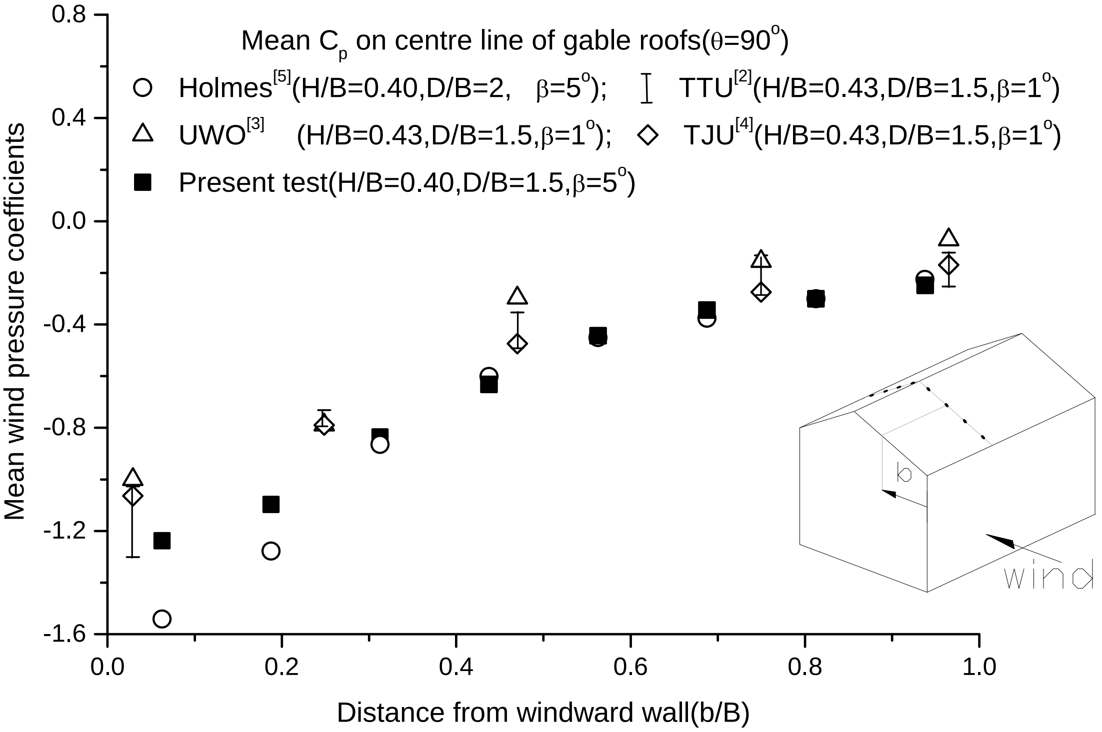


Figure 4. Comparison of mean wind pressure coefficients with those in the literature

Basically, the present test data fitted well with those in the literature, although there were minor differences since the tested wind fields and the tested models were not exactly the same.

In Figure 4, the present test data were the same as those of Holmes on the leeward roof, while there were some differences near the windward eave. This is possibly related to the difference between the models used. The depth/breadth ratio of Holmes models was 2 while that of the present one was 1.5.

The negative pressure coefficients in the present wind tunnel test are a little larger than those of TTU, UWO and TJU. This is possibly related to the different turbulences of the wind fields. The turbulence intensities at the model height in the present test were about 0.25 while those of TTU, UWO and TJU were about 0.19.

4 Test Data Process

The measured voltage signals were translated into time series of wind pressure with the calibrating data of the pressure sensors at first. After that, the effect of the tube system on the measured wind pressure was eliminated by dividing the transfer function from the power spectra of the raw wind pressure. The transfer function of the tube system shown in Figure 5 was identified with a frequency sweep technique.

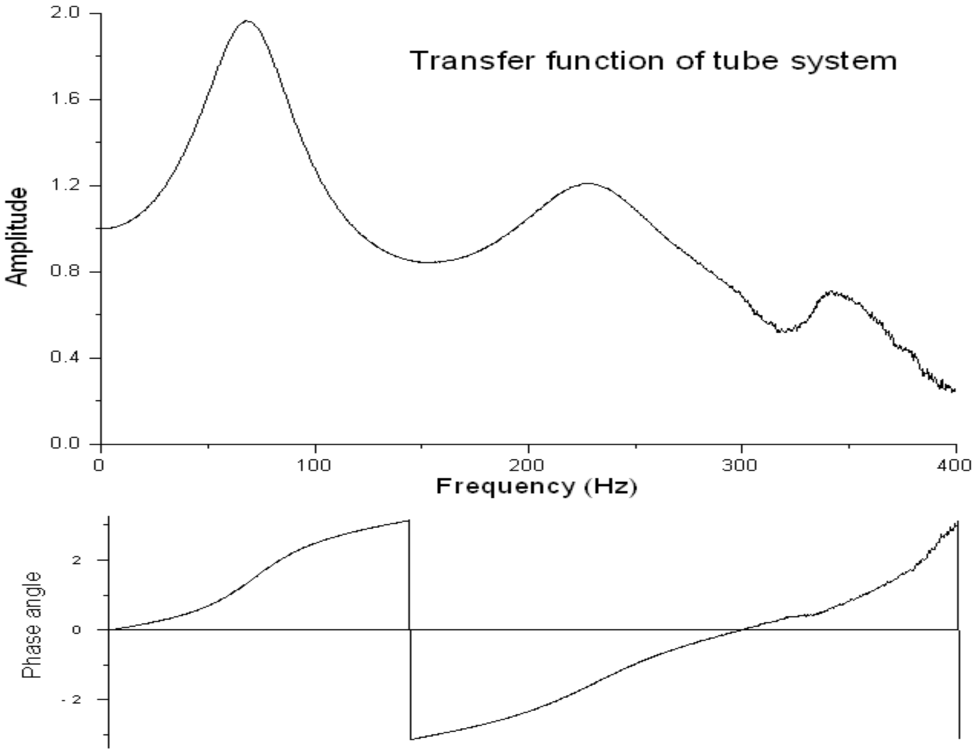


Figure 5. Transfer function of tube system

The time series of wind pressure coefficients is calculated as:

$$C_{p\_ori}(i,t) = p(i,t) / p_H \tag{1}$$

where $C_{p\_ori}(i,t)$ is original wind pressure coefficients at measured tap i at time t; $p(i,t)$ is measured wind pressure at tap i at time t; p_H is the reference wind pressure of the approaching wind velocity at the average roof height, H, defined in Figure 2.

In order to make the wind pressure coefficients correspond to some duration, the time series of wind pressure coefficients were moving averaged as:

$$C_p(i,t) = \overline{C_{p\_ori}(i, t-\Delta t/2 \sim t+\Delta t/2)} \tag{2}$$

where Δt is the duration of the wind pressure coefficients.

The database shows three types of data: statistical values of local wind pressure coefficients, statistical values of area averaged wind pressure coefficients and time series of point wind pressure coefficients. The time series data were moving averaged every 0.006s, corresponding to 0.2s in full scale. The statistical values of area averaged wind pressure coefficients were calculated with moving averaged every 0.006s corresponding to durations of 0.2 second in full scale else. The statistical values of local wind pressure coefficients were calculated with point wind pressure coefficients moving averaged every 0.03s so that their durations were 1.0 second in full scale. According to an expedient formula by Lawson [6], the corresponding general size is roughly estimated at 5m for this duration at the design wind velocity of 22m/s. To design cladding or components with a size smaller than 5m, one can calculate its extreme wind loads based on the original time series of point wind pressure coefficients given in the database for the corresponding duration.

5 Database system

The statistical values of local wind pressure coefficients are expressed as contours in the database system. Statistical values of area averaged pressure coefficient are expressed as graphs versus wind direction angle. Time series of point wind pressure coefficients are stored in MATLAB data format.

5.1 Statistical values of local wind pressure coefficients

Contours of the statistical values of local wind pressure coefficients calculated from Equation (2) with a duration of 1s in full scale were drawn. There were four types of statistical values shown: mean, RMS, positive extreme and negative extreme.

The mean and RMS values were the averaged values of ten samples:

$$\overline{C_p} = \frac{1}{10}\sum_{n=1}^{10}\overline{C_p}(n) \tag{3}$$

$$\tilde{C}_p = \frac{1}{10}\sum_{n=1}^{10}\tilde{C}_p(n) \tag{4}$$

where, $\overline{C_p}(n)$ and $\tilde{C}_p(n)$ are the mean and RMS values of the time series of the *n*th sample.

The extreme values were calculated by the Cook & Mayne method [7], where the extreme distribution of wind pressure coefficients was assumed as a Fisher-Tippett Type 1 (FT1) distribution:

$$\hat{C}_p = U_{\hat{C}p} + 1.4 / a_{\hat{C}p} \tag{5}$$

where, $U_{\hat{C}p}$ *and* $1/a_{\hat{C}p}$ are the mode and dispersion of the Fisher-Tippett Type 1, respectively, which can be calculated by the Best Linear Unbiased Estimators (BLUE) [8] as：

$$U_{\hat{C}p} = \sum_{i=1}^{10} a_i X_i \tag{6}$$

$$1/a_{\hat{C}p} = \sum_{i=1}^{10} b_i X_i \tag{7}$$

where, x_i is the *i*th value of the ascending array of maximum values of 10 samples and a_i and b_i are given by Table 2.

Table 2, coefficients of BLUE for FT 1 distribution (for 10 samples)

i	1	2	3	4	5	6	7	8	9	10
a_i	0. 22	0. 16	0. 13	0. 11	0. 096	0. 081	0. 067	0. 054	0. 042	0. 029
b_i	−0. 35	−0. 091	−0. 019	0. 022	0. 049	0. 066	0. 077	0. 083	0. 084	0. 078

Equation (5) expresses positive extreme values, and it can also be used to calculate negative extreme values. The probability of exceedence of the extreme values calculated from Equation (5) is 22%.

Figure 6 shows an example of the contours of statistical values of local wind pressure coefficients. Values not at the measured points shown in Figure 5 were interpolated from measured values.

5.2 Statistical values of area averaged wind pressure coefficients

The contours in Section 5.1 are based on statistical values of wind pressure coefficients at measured points. Mean wind force coefficients of wind force on a wall or roof surface can be calculated from mean values of point wind pressure coefficients. However, the RMS and extreme values of wind force cannot be evaluated in this way because of the correlation among point wind pressures.

For convenience, the statistical values of area averaged wind pressure coefficients on each roof or wall surface were shown in this database too.

The area averaged wind pressure coefficients on a roof or wall surface were calculated from:

$$C_F(j,t) = \sum_{i=1}^{N_j} \left(C_p(i,t).A_i \right) / \sum_{i=1}^{N_j} A_i \tag{8}$$

where, $C_F(j,t)$ is the area averaged wind pressure coefficient on Surface j at time t; $C_p(i,t)$ is the wind pressure coefficient at point i at time t， obtained from Equation (2) with a duration of 0.2s in full scale; A_i is the effective area of wind pressure measured at point i; and N_j is the number of measured points on Surface j. The number of surface, j, was defined in Figure 2.

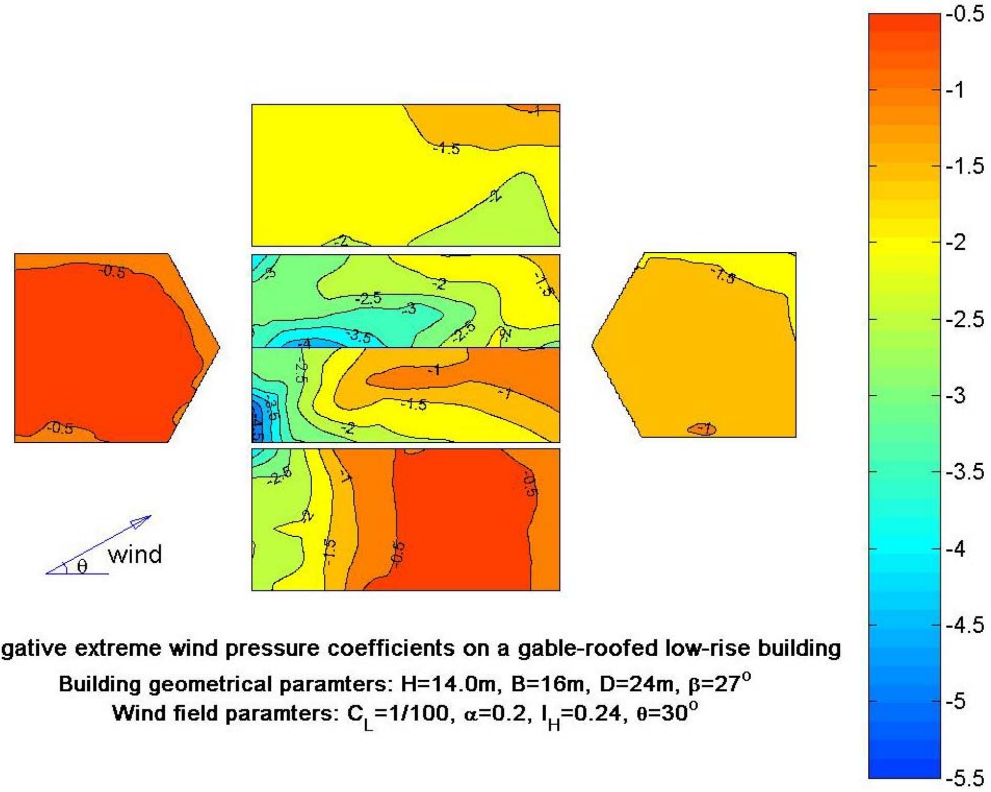


Figure 6. An example of contours of statistical values of local wind pressure coefficients

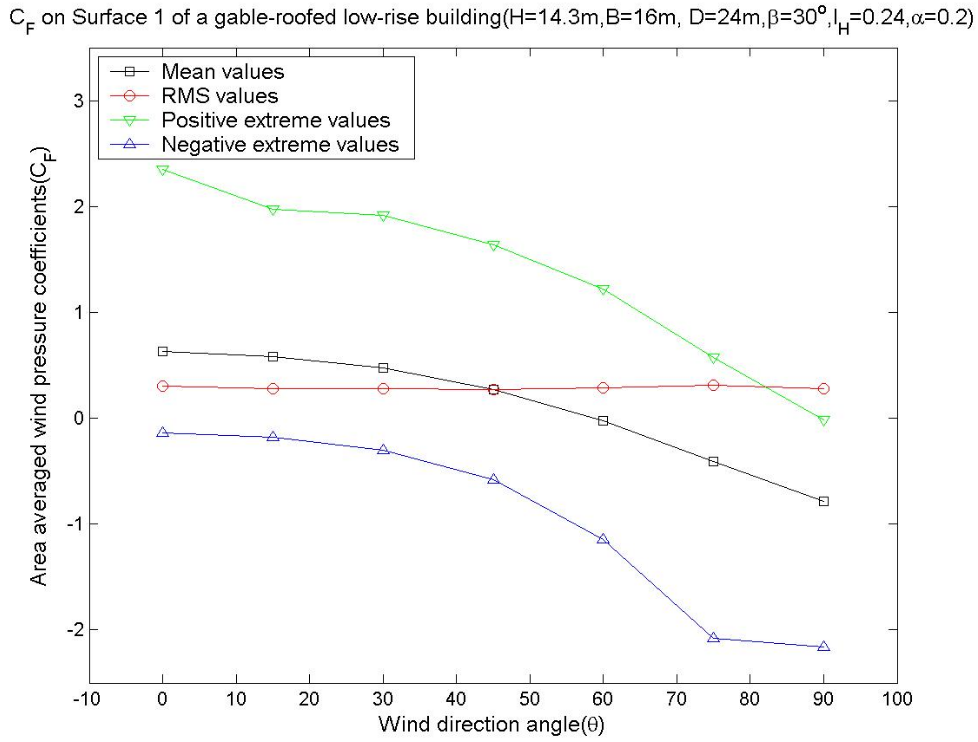


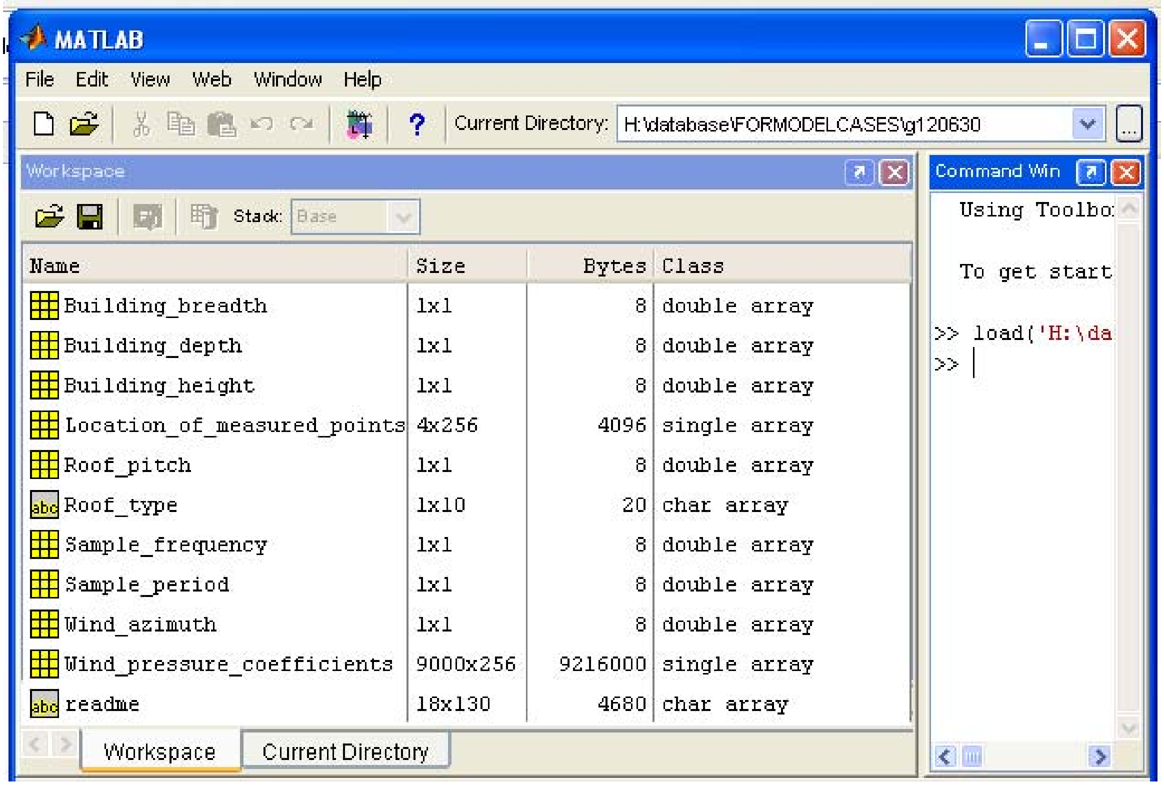
Figure 7. An example of the statistical values of area averaged wind pressure coefficients

The mean, RMS, positive extreme and negative extreme values of area averaged wind pressure coefficients on each roof or wall surface were calculated from $C_F(j,t)$ by the methods used in Section 5.1. The graphs of those values versus wind direction angle are shown on the website as Figure 7.

5.3 Time series of point wind pressure coefficients

One of the ten samples of time series of synchronous-measured point wind pressure coefficients at each measurement point for each test case calculated from Equation (2) with a duration of 0.2s in full scale, which can be used to analyze the dynamic responses of the low-rise buildings, are shown in this database.

The data are saved in MATLAB data format, as shown in Figure 8. There are 11 values saved in each data file, including the information of model geometrical parameters, wind characteristics, locations of measured points, data sample and time series of wind pressure coefficients. There is also a character constant named README, whose content is some sentences telling reader the detail of the wind tunnel test and the test data.



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Stack: Base

Name	Size	Bytes	Class
Building_breadth	1x1	8	double array
Building_depth	1x1	8	double array
Building_height	1x1	8	double array
Location_of_measured_points	4x256	4096	single array
Roof_pitch	1x1	8	double array
Roof_type	1x10	20	char array
Sample_frequency	1x1	8	double array
Sample_period	1x1	8	double array
Wind_azimuth	1x1	8	double array
Wind_pressure_coefficients	9000x256	9216000	single array
readme	18x130	4680	char array

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Figure 8. Format of time series of point wind pressure coefficients

6. Usage of data

The time series data of point wind pressure coefficients can be used to analyze the dynamic responses of low-rise buildings.

The statistical values of local wind pressure coefficients are also useful for the design of cladding and components such as window panes, furring strips, purlins, and so on.

The statistical values of area averaged wind pressure coefficients on a surface can be used to design structural frames such as girders and pillars.

References

[1] AIJ Recommendations for Loads on Buildings (in Japanese), Architectural Institute of Japan, 2004

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