Test Data of High-rise Building Wind Tunnel Tests from Dr. Liangbo

QUAN Yong

In order to study the power spectra and time-spatial correlations of along-wind, across-wind and torsional wind forces loaded on tall buildings with rectangular cross-section, Doctor Liangbo took a series of local wind pressure measurement wind tunnel tests and high frequency balance wind tunnel tests for 6 building models in 1995. In his wind tunnel test report, he showed wind force coefficients of all models, and power spectra, correlations and corresponding mathematical models of generalized wind forces, local wind forces and base forces.
In order to build a wind loads database of buildings and structures, I attempt to pick up some useful test data from his report today.

1.Wind Tunnel Test Introduction

1.1. Wind Tunnel

The wind tunnel test is carried out in the Boundary-Layer Wind Tunnel with 3.1 meters wide and 2.0 meters high and 16 meters long, Wind Engineering Institute.

1.2. Test Wind Field

The blocks and spires are used to generate a boundary layer. The wind tunnel flow features, for example: mean wind speed profile, turbulence intensity and turbulence scale, are shown in Fig.1, According to “AIJ Recommendations for Loads on Buildings”, the experimental flow features belong in terrain roughness category 2.

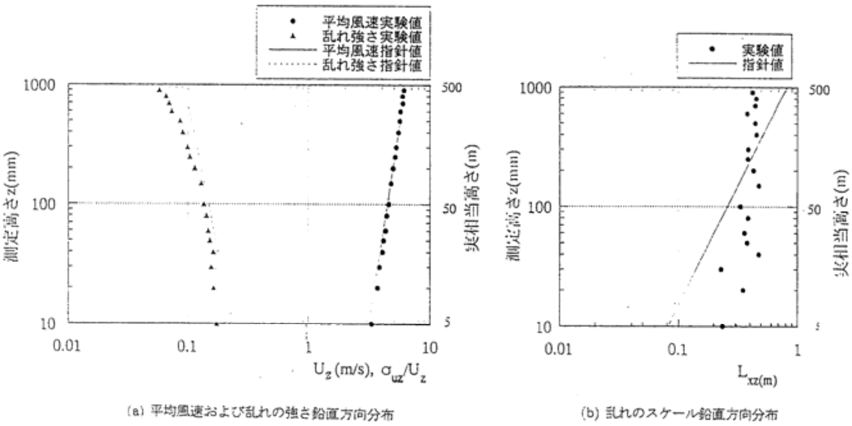


Fig.1 Features of Testing Wind Field

1.3. Testing Models

The length scale of the experimental model was set at 1/500. The dimensions the six testing models, whose cross-section areas are same, were given in the Tab. 1 below.

Tab.1 Model Dimensions

Model Name	Breadth B (mm)	Depth D (mm)	Height H (mm)	Side Ratio D/B	Aspect Ratio $H/\sqrt{BD}$
M1-3	100	100	300	1.0	3
M1-4	100	100	400	1.0	4
M1-5	100	100	500	1.0	5
M1.6-4	79	126	400	1.6	4
M2-4	71	142	400	2.0	4
M3-4	58	173	400	3.0	4
M0.6-4	126	79	400	0.6	4
M0.5-4	142	71	400	0.5	4
M0.3-4	173	58	400	0.3	4

1.4. Measuring Method

1.4.1. Local wind forces

The investigation of local wind forces included the measurement of along-wind force, across-wind force and torsional moment. The levels in the vertical direction are shown in Fig.2.

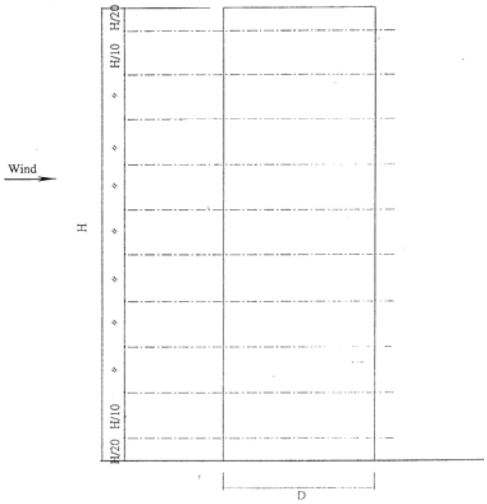


Fig.2 Measure Levels of Local Forces in the Vertical Direcion

The measured points of each horizontal level were shown from Fig. 3~4.

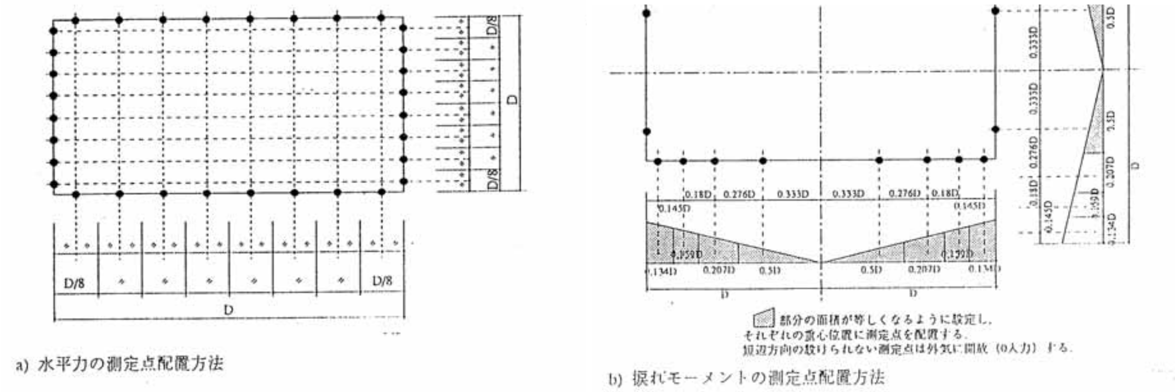


Fig.3 Measure Points of Local Forces of Each Horizontal Level

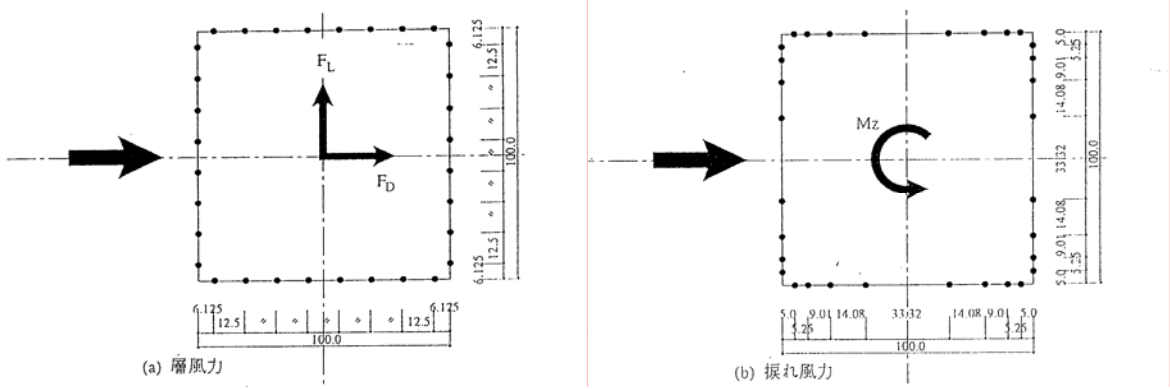


Fig.4 Measure Points of Local Wind Forces (D:B=1:1)

Fig. 5 showed the multi-hold method for obtaining wind pressure.

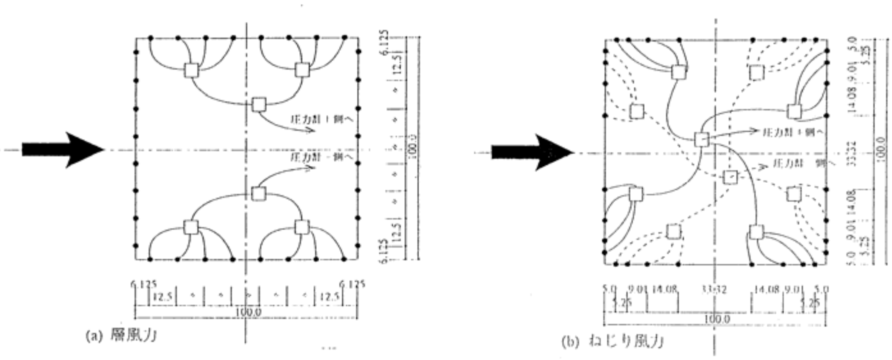
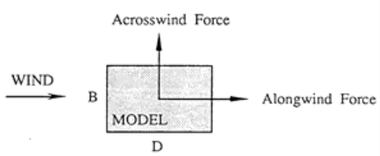


Fig.5 Multi-hold Method for Obtaining Wind Pressure

The time interval of sampling point was 1.6ms, and the total number of sampled points is 16992. So the sampled length is about 27 seconds.
The mean and fluctuating wind force coefficients of local wind forces were defined as:

$$\overline{C}_{F_D}(z)=\overline{F}_D(z)/(Bq_H);\quad \overline{C}_{F_L}(z)=\overline{F}_L(z)/(Bq_H);\quad \overline{C}_{M_Z}(z)=\overline{M}_Z(z)/(BDq_H)$$
$$C'_{F_D}(z)=\sigma_{F_D}(z)/(Bq_H);\quad \overline{C}_{F_L}(z)=\sigma_{F_L}(z)/(Bq_H);\quad \overline{C}_{M_Z}(z)=\sigma_{M_Z}(z)/(BDq_H) \tag{1}$$

in which,



$\overline{F}_D(z)$ and $\overline{F}_L(z)$: mean wind forces at height z;

$\sigma_{F_D}(z)$ and $\sigma_{F_L}(z)$: standard deviations of wind forces at height z;

$\overline{M}_Z(z)$ and $\sigma_{M_Z}(z)$: mean value and standard deviation of torsional moment at height z;

B, D and q_H: projected breadth of model, depth of model and velocity pressure at the top of model.

1.4.2. Base forces

The definition of five components of base force was shown in Fig.9.

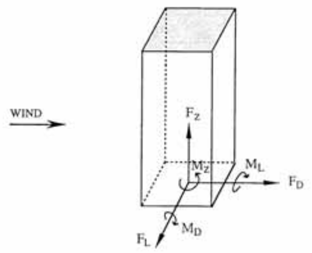


Fig.9 Definition of five components of base force

The time interval of sampled points is 6.2ms, and the total number of sampled point is 10000. So the sampling length is 62 seconds.
The mean and fluctuation wind force coefficients of base forces were defined as:

$$\overline{C}_{F_D}=\overline{F}_D/(BHq_H);\overline{C}_{F_L}=\overline{F}_L/(BHq_H);\overline{C}_{M_D}=\overline{M}_D/(BH^2Dq_H);\overline{C}_{M_L}=\overline{M}_L/(BH^2Dq_H);\overline{C}_{M_Z}=\overline{M}_Z/(BH^2Dq_H)$$
$$C_{F_D}=\sigma'_{F_D}/(BHq_H);C_{F_L}=\sigma'_{F_L}/(BHq_H);C_{M_D}=\sigma'_{M_D}/(BH^2Dq_H);C_{M_L}=\sigma'_{M_L}/(BH^2Dq_H);C_{M_Z}=\sigma'_{M_Z}/(BH^2Dq_H) \tag{2}$$

in which,

$\overline{F}_D$ and σ_{F_D} : mean value and standard deviation of base shear force in along-wind direction;

$\overline{F}_L$ and σ_{F_L} : mean value and standard deviation of base shear force in across-wind direction;

$\overline{M}_D$ and σ_{M_D} : mean value and standard deviation of across-wind base overturning moment;

$\overline{M}_L$ and σ_{M_L} : mean value and standard deviation of along-wind base overturning moment;

$\overline{M}_Z$ and σ_{M_Z} : mean value and standard deviation of torsional moment;

H, B, D and q_H: height, breadth, depth of model and velocity pressure at the top of model.

2. Test Results

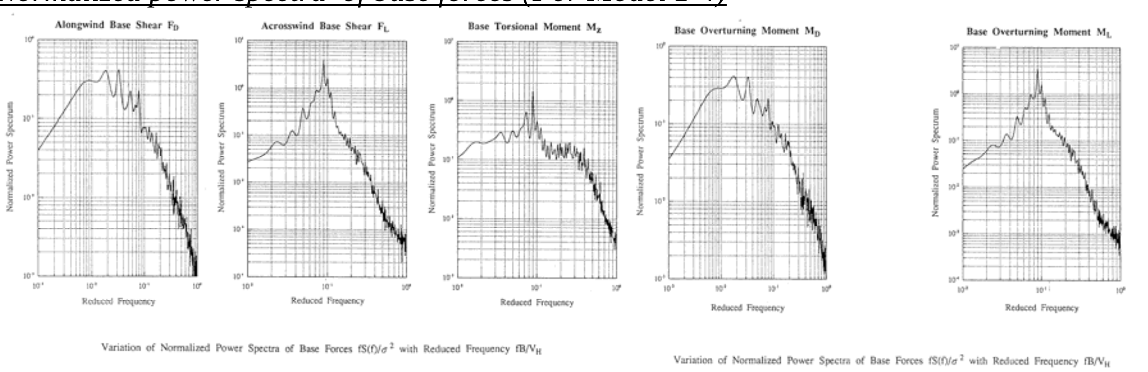
2.1 Base Force (For Model 1-4)

2.1.1 Wind force coefficients obtained from base forces (For Model 1-4)

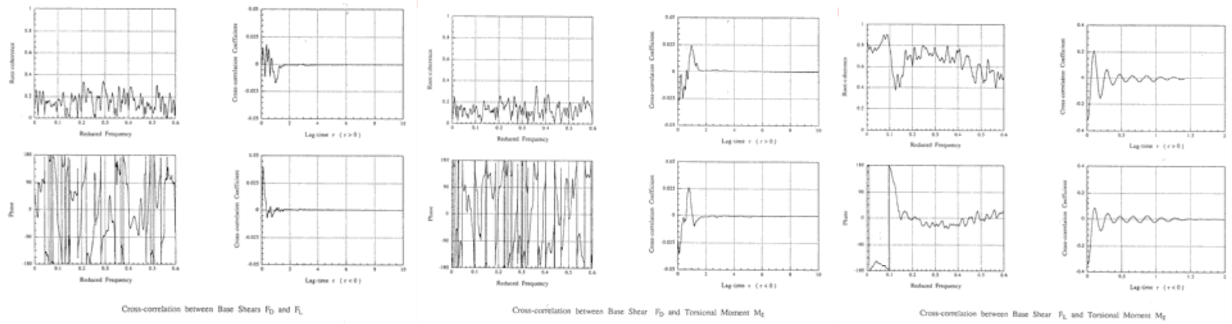
Tab.2 Wind force coefficients obtained from base forces

Model	$\bar{C}_{F_D}$	C'_{F_D}	C'_{F_L}	C'_{M_Z}	$\bar{C}_{\hat{F}_D}$	$C'_{\hat{F}_D}$	$C'_{\hat{F}_L}$
M1-4	1.070	0.184	0.279	0.028	0.586	0.101	0.143

2.1.2 Normalized power spectra of base forces (For Model 1-4)



2.1.3 Cross-correlation between different base forces (For Model 1-4)



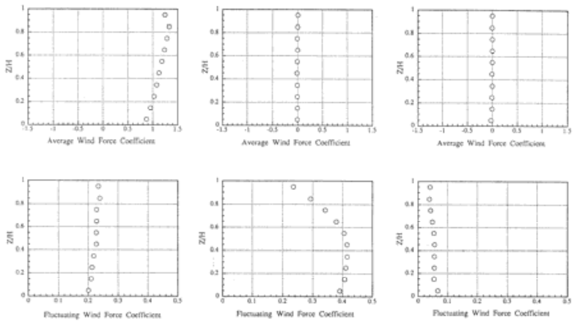
2.2 Local Wind Force

2.2.1 Wind force coefficients obtained from local wind force

Tab.3 Wind force coefficients obtained from local wind force

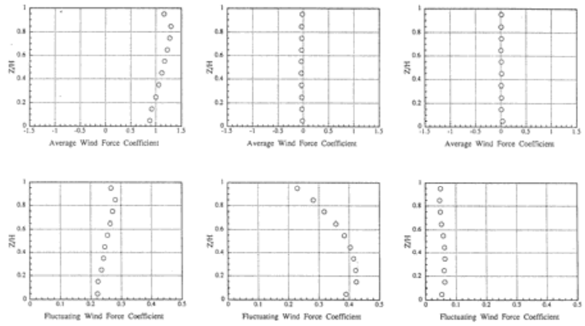
Model	$\bar{C}_{F_D}$	C'_{F_D}	C'_{F_L}	C'_{M_Z}
M1-3	1.111	0.221	0.327	0.044
M1-4	1.134	0.184	0.329	0.027
M1-5	1.216	0.192	0.325	0.032
M1.6-4	1.011	0.188	0.363	0.065
M2-4	0.895	0.146	0.330	0.075
M3-4	0.894	0.127	0.387	0.067
M0.6-4	1.257	0.200	0.267	0.042
M0.5-4	1.233	0.181	0.151	0.045
M0.3-4	1.243	0.164	0.061	0.041

2.2.2 Local wind force coefficients



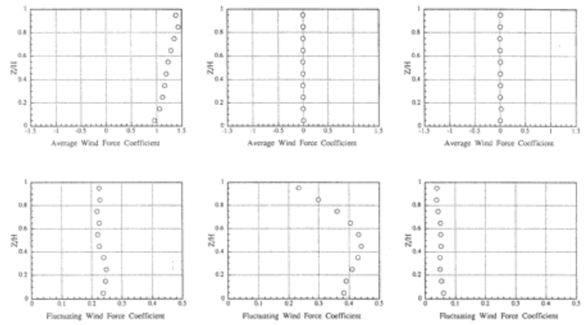
1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

Local Wind Force Coefficients (Model = M1-4)



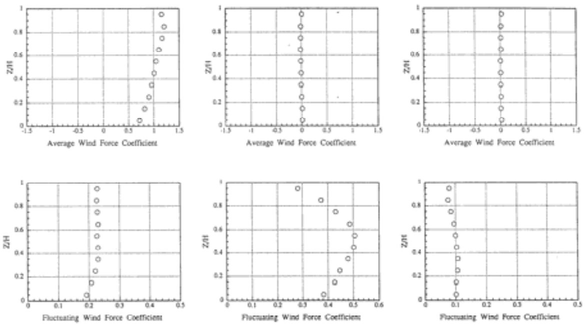
1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

Local Wind Force Coefficients (Model = M1-3)



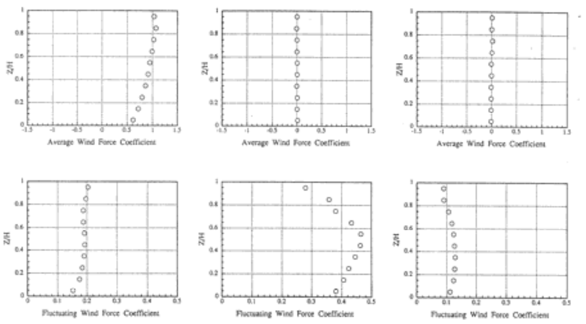
1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

Local Wind Force Coefficients (Model = M1-5)



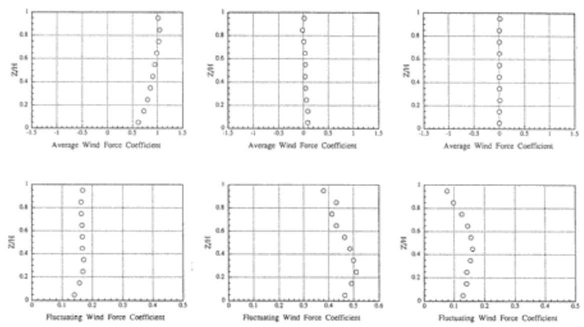
1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

Local Wind Force Coefficients (Model = M1.6-4)



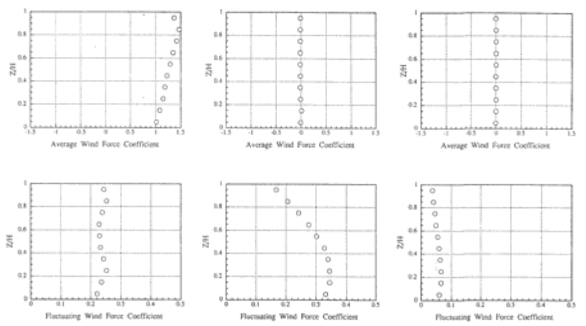
1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

Local Wind Force Coefficients (Model = M2-4)



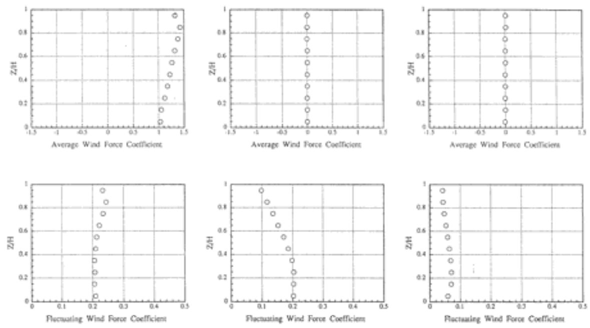
1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

Local Wind Force Coefficients (Model = M3-4)



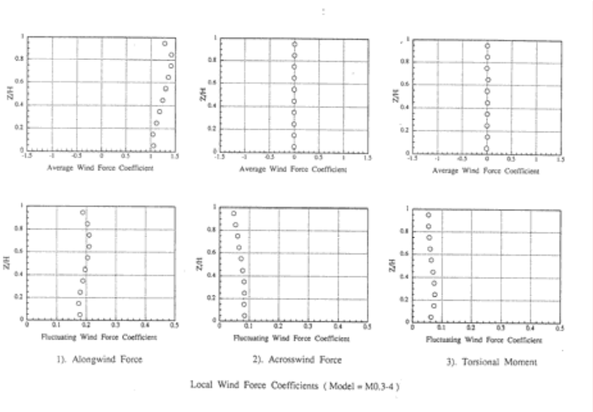
1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

Local Wind Force Coefficients (Model = M0.6-4)

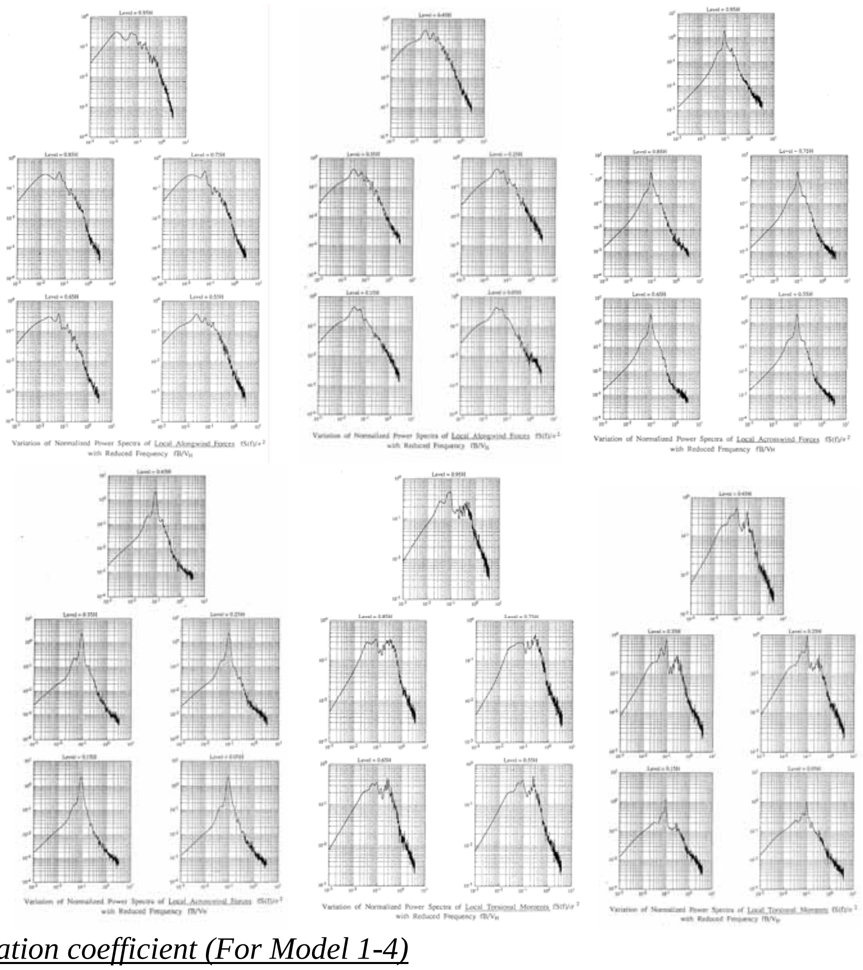


1). Alongwind Force 2). Acrosswind Force 3). Torsional Moment

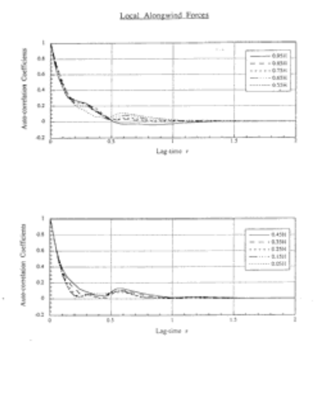
Local Wind Force Coefficients (Model = M0.5-4)



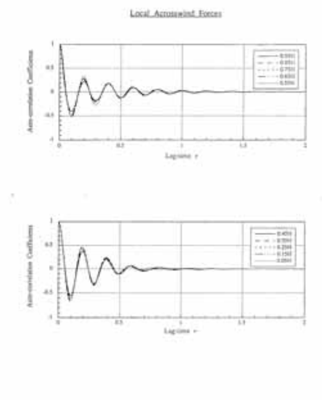
2.2.3 Normalized power spectra of local wind forces (For Model 1-4)



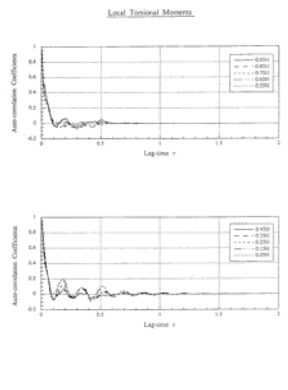
2.2.4 Auto-correlation coefficient (For Model 1-4)



Variation of Auto-correlation Coefficients of Local Alongwind Forces with Lag-time



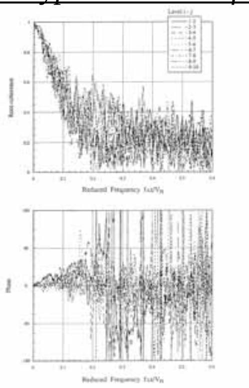
Variation of Auto-correlation Coefficients of Local Acrosswind Forces with Lag-time



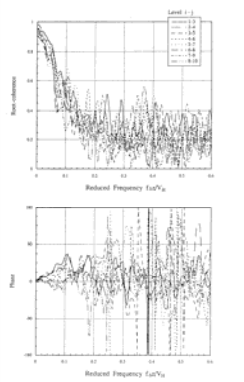
Variation of Auto-correlation Coefficients of Local Torsional Moments with Lag-time

2.2.5 Root-correlation and phase (For Model 1-4)

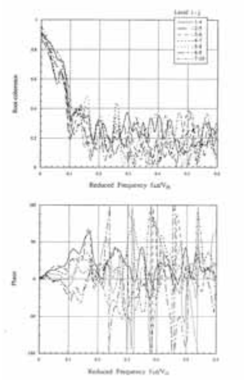
2.2.5.1 Same type local wind forces between different levels (For Model 1-4)



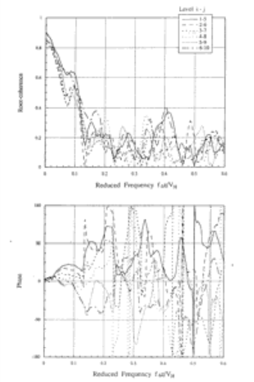
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = H/10$)



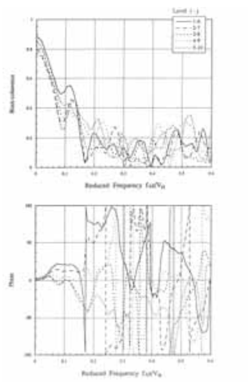
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 2 \times H/10$)



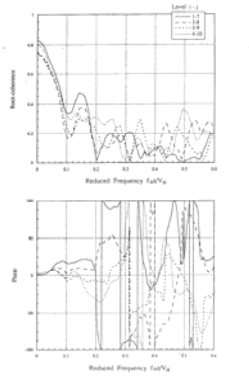
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 3 \times H/10$)



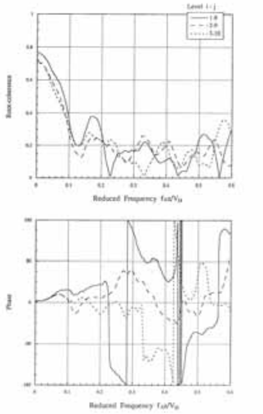
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 4 \times H/10$)



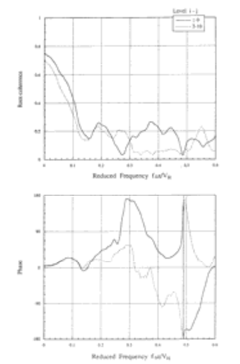
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 5 \times H/10$)



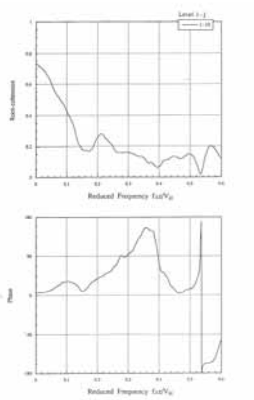
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 6 \times H/10$)



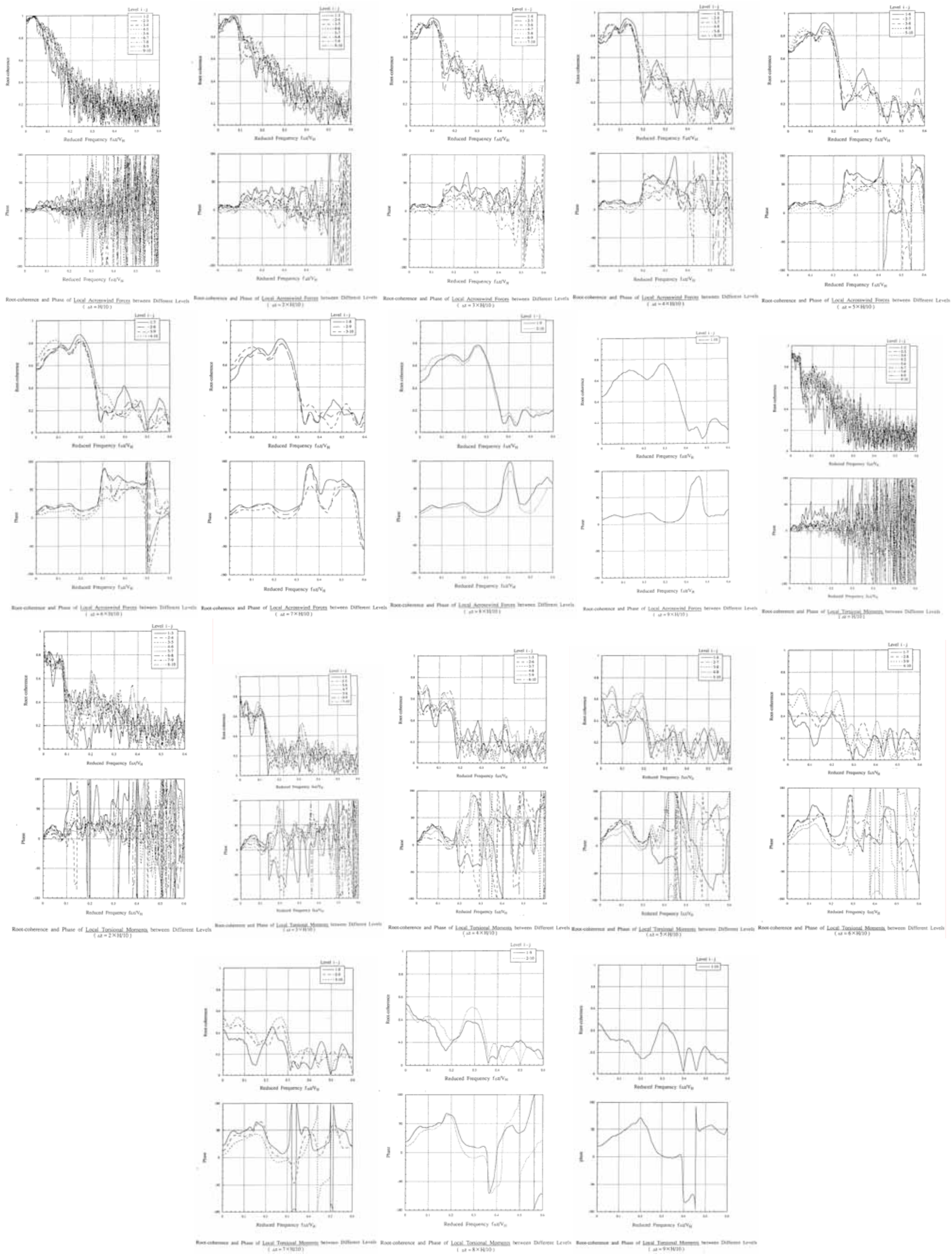
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 7 \times H/10$)



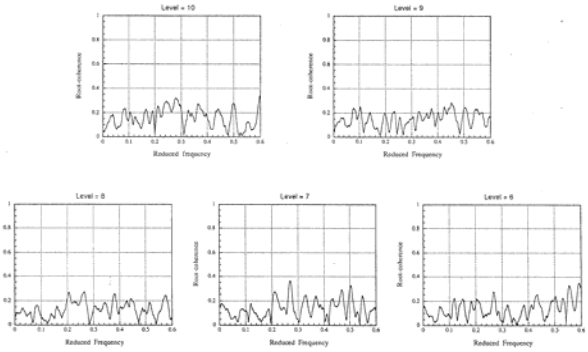
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 8 \times H/10$)



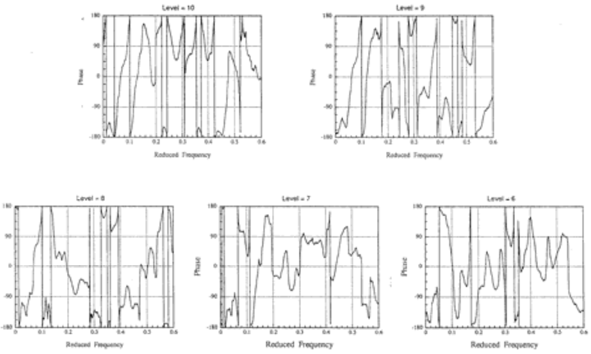
Root-coherence and Phase of Local Alongwind Forces between Different Levels ($\Delta z = 9 \times H/10$)



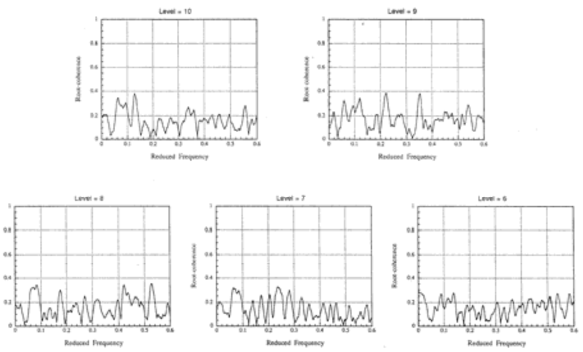
2.2.5.2 Different type local wind forces between same level (For Model 1-4)



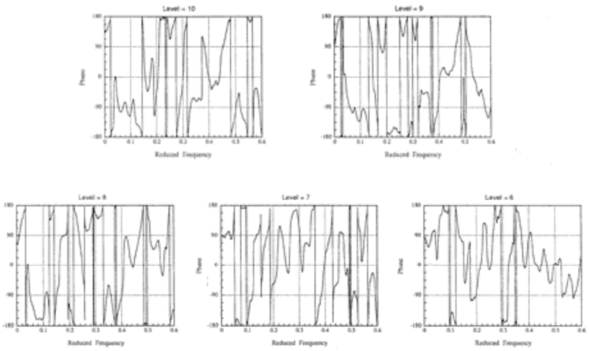
Root-coherence between Alongwind Force and Acrosswind Force at the Same Level
(Reduced Frequency = fB/V_H)



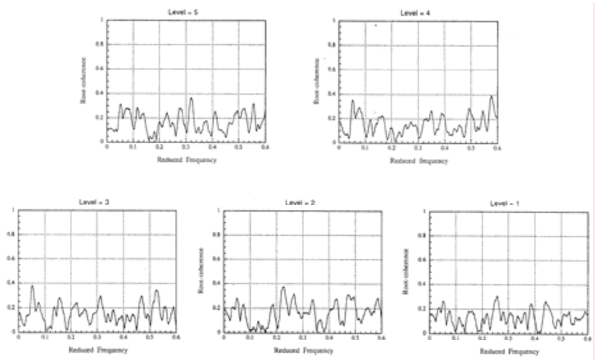
Phase between Alongwind Force and Acrosswind Force at the Same Level
(Reduced Frequency = fB/V_H)



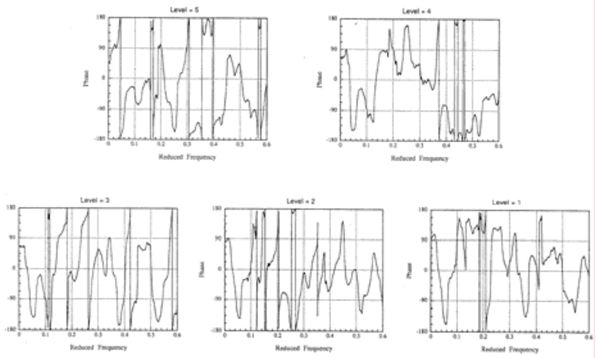
Root-coherence between Alongwind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)



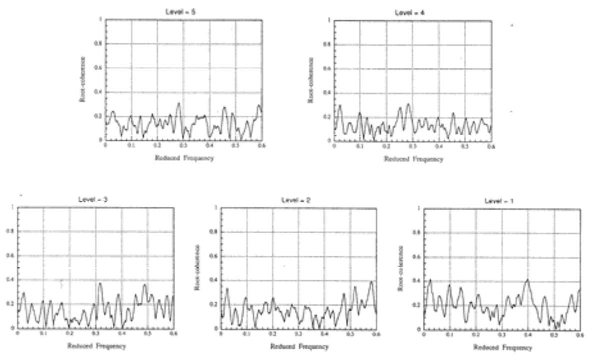
Phase between Alongwind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)



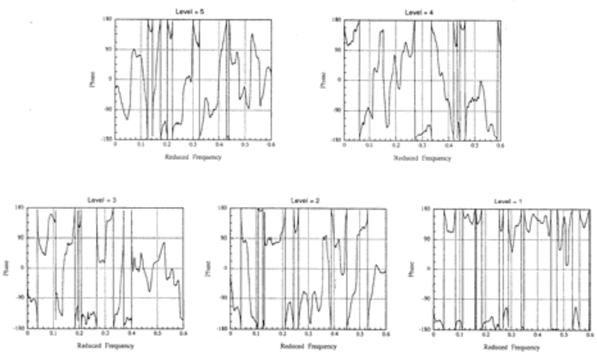
Root-coherence between Alongwind Force and Acrosswind Force at the Same Level
(Reduced Frequency = fB/V_H)



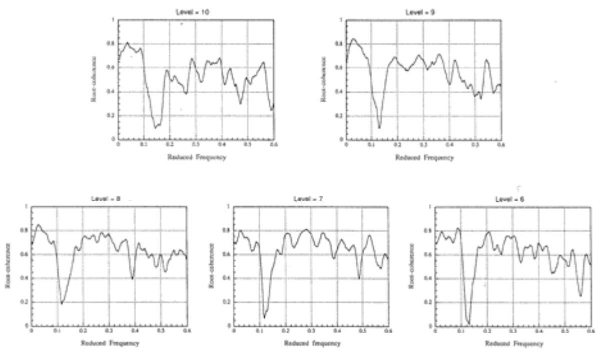
Phase between Alongwind Force and Acrosswind Force at the Same Level
(Reduced Frequency = fB/V_H)

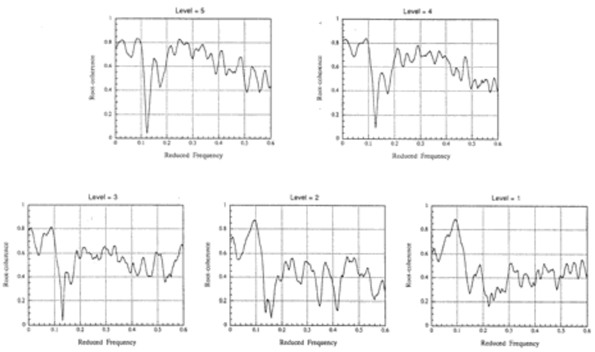


Root-coherence between Alongwind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)



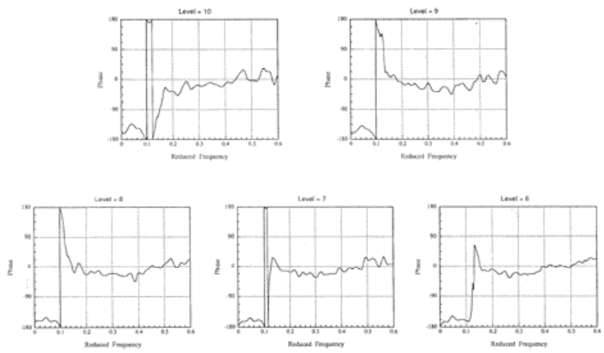
Phase between Alongwind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)

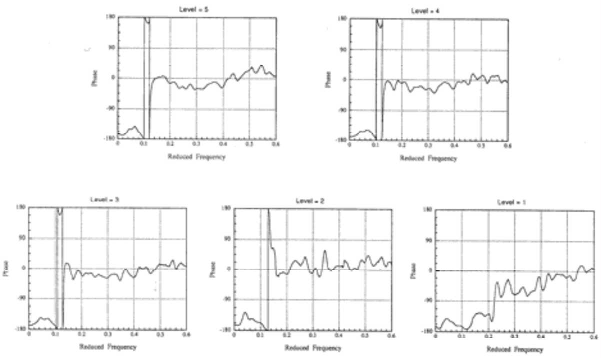




Root-coherence between Acrosswind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)

Root-coherence between Acrosswind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)





Phase between Acrosswind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)

Phase between Acrosswind Force and Torsional Moment at the Same Level
(Reduced Frequency = fB/V_H)

3. Mathematical Model of Wind Forces

3.1 Root-coherence and Phase

3.1.1 Base forces

The root-coherence and phase between across-wind base shear and torsional base moment of models with square cross-section are given by following equations:

$$\sqrt{COH} = 0.9\exp(-K\bar{f}) \qquad K = 1, \quad \bar{f} = fB/V_H \tag{3}$$

$$\Phi = \begin{cases} -16000(f - \bar{f}_0/2)^2 + 220, & if \quad \bar{f} < \bar{f}_0 = 0.1 \\ 180\exp[-50(\bar{f} - \bar{f}_0)], & if \quad f \geq \bar{f}_0 \end{cases} \tag{4}$$

in which, Φ is in degree, f is the frequency (Hz).

3.1.2 Different type local wind forces at the same level

The root-coherence and phase between local across-wind force and local torsional moments at level 3H/4 are given by following equations:

$$\sqrt{COH} = 0.8\exp(-K\bar{f}) \qquad K = 0.5, \quad \bar{f} = fB/V_H \tag{5}$$

$$\Phi = \begin{cases} -180 - 480\bar{f} & if \;\; D/B < 1 \; and \;\; \bar{f} < 0.25 \\ 60 & if \;\; D/B < 1 \; and \;\; \bar{f} \geq 0.25 \\ -160 & if \;\; D/B = 1 \; and \;\; \bar{f} < \bar{f}_0 = 0.14 - 0.01(H/D) \\ 20\left(\bar{f} - \bar{f}_0\right) & if \;\; D/B = 1 \; and \;\; \bar{f} \geq \bar{f}_0 \\ -160 + 800\bar{f} & if \;\; D/B > 1 \; and \;\; \bar{f} < 0.2 \\ 0 & if \;\; D/B > 1 \; and \;\; \bar{f} < 0.2 \end{cases} \tag{6}$$

3.1.3 Same type local wind forces between different levels

3.1.3.1 Local along-wind force

The root-coherence and phase between local along-wind forces between level i and level j are given by following equations:

$$\sqrt{COH} = R_0 \exp(-K\bar{f})$$

$$K = 6, \quad \bar{f} = \Delta z f / V_H, \; \Delta z = |z_i - z_j|, \; R_0 = \begin{cases} 1.0 - 0.11\Delta z / H, \; if \quad H/\sqrt{BD} \le 3 \\ 1.0 - 0.20\Delta z / H, \; if \quad H/\sqrt{BD} > 3 \end{cases} \tag{7}$$

$$\Phi = 0 \tag{8}$$

in which, f is the frequency (Hz), and

z_i, z_j are heights of level i and j

V_H is mean wind speed at the top of model

3.1.3.2 Local across-wind force

The root-coherence and phase between local along-wind forces between level I and level j are given by following equations:

$$\sqrt{COH} = \begin{cases} \begin{cases} \bar{f} + [1 - 0.6(\Delta z / H)] & if \;\; \bar{f} < \bar{f}_0 \; and \;\; D/B < 3 \\ R_0 & if \;\; \bar{f} < \bar{f}_0 \; and \;\; D/B \ge 3 \end{cases} \\ R_0 \exp[-K(\bar{f} - \bar{f}_0)] \quad if \;\; \bar{f} \ge \bar{f}_0 \end{cases} \tag{9}$$

$$K = 4, \;\; R_0 = 1.0 - 0.27(\Delta z / H), \quad \bar{f}_0 = 0.33(\Delta z / H), \quad \bar{f} = f\Delta z / V_H, \quad \Delta z = |z_i - z_j|$$

$$\Phi = \begin{cases} 0.4(\Delta z / H) \times 90 & if \;\; \bar{f} < \bar{f}_0 \\ \Phi_0 \exp[-K(\bar{f} - \bar{f}_0)] & if \;\; \bar{f} \ge \bar{f}_0 \end{cases} \tag{10}$$

$$K = 4, \;\; \Phi_0 = (\Delta z / H) \times 180, \;\; \bar{f}_0 = 0.5(\Delta z / H), \; \bar{f} = f\Delta z / V_H, \; \Delta z = |z_i - z_j|$$

3.1.3.3 Local torsional moment

The root-coherence and phase between local torsional moments between level I and level j are given by following equations:

$$\sqrt{COH} = \begin{cases} R_0 & if \;\; \bar{f} < \bar{f}_0 \\ R_0 \exp[-K(\bar{f} - \bar{f}_0)] & if \;\; \bar{f} \ge \bar{f}_0 \end{cases}$$

$$K = 4, \; \bar{f}_0 = 0.33(\Delta z / H), \; \bar{f} = f\Delta z / V_H, \; \Delta z = |z_i - z_j| \tag{11}$$

$$R_0 = \begin{cases} 0.94 - 0.6(\Delta z / H) \;\; if \;\; H/\sqrt{BD} \ge 4 \; and \; D/B = 1 \\ 1.0 - 0.65(\Delta z / H) \;\; otherwise \end{cases}$$

$$\Phi = \begin{cases} \left[20\bar{f} + 1.5(\Delta z / H)\right] \times 90/4 & if \quad \bar{f} < \bar{f}_0 \\ \Phi_0 \exp[-K(\bar{f} - \bar{f}_0)] & if \quad \bar{f} \ge \bar{f}_0 \end{cases} \tag{12}$$

$$K = 20, \;\; \Phi_0 = 6.1(\Delta z / H) \times 90/4, \;\; \bar{f}_0 = 0.23(\Delta z / H), \; \bar{f} = f\Delta z / V_H, \; \Delta z = |z_i - z_j|$$

3.2 Normalized Power Spectra

3.2.1 Local along-wind force

The normalized power spectra of local along-wind forces at any level of building are given by following equations:

$$\frac{fS_{FD}(z,f)}{\sigma_{FD}^2} = \frac{f\xi\beta}{\left[1 + \eta(f\beta)^2\right]^{1.08}} \left[1 + \left(\frac{z}{H}\frac{fB}{\bar{V}(z)}\right)^2\right]^{-1} \tag{13}$$

$$L_H = 100(H/30)^{0.5}, \quad \bar{V}(z) = \bar{V}_{10}(z/10)^{\alpha}$$

$$if \;\; D/B \ge 1: \beta = (L_H / V_H)(D/B)^{-0.5}(z/H)^{0.15}, \xi = 9.3 \quad , \quad \eta = 142$$

$$if \;\; D/B < 1: \beta = (L_H / V_H)(D/B)^{-0.5} \quad , \quad \xi = 9.3(D/B)^{-0.3}, \eta = 142(D/B)^{-0.5}$$

in which, $\bar{V}(z)$ = mean wind speed at height z

$\bar{V}_{10}$ = mean wind speed at height 10m

α = power law index of vertical profile of mean wind speed

L_H = turbulence scale at height H

3.2.2 Local across-wind force

The normalized power spectra of local across-wind forces at any level of building are given by following equations:

$$\frac{fS_{FL}(f)}{\sigma_{FL}^2} = \frac{fS_{ST}(f)}{\sigma_{ST}^2} + \frac{fS_{VS}(f)}{\sigma_{VS}^2}$$

$$\frac{fS_{ST}(f)}{\sigma_{ST}^2} = B_1 \frac{\bar{f}_S / k}{\left[1+\xi\left(\bar{f}_S / k\right)^c\right]^{2.5}} + T_1 \frac{\left(\bar{f}_S / k\right)^3}{\left[1+0.48\left(\bar{f}_S / k\right)^2\right]^7}$$

$$\frac{fS_{VS}(f)}{\sigma_{VS}^2} = \frac{B_2}{\delta\sqrt{2\pi}} \exp\left[-0.5\left(\frac{\ln \bar{f}_s + 0.5\delta^2}{\delta}\right)^2\right]$$

$$\bar{f}_s = f / f_s \ , \ f_s = \frac{0.12V_H / B}{\left[1+0.38(D/B)^2\right]^{0.89}} \ , \ \xi = 0.62e^{-0.3\bar{z}}$$

$$k = \begin{cases} 1.3/\sqrt{D/B} & if \ D/B \geq 1 \\ 1.3/\sqrt{1.5D/B} & if \ D/B < 1 \end{cases}$$

$$\eta = \begin{cases} 1.0 & if \ D/B \leq 1 \\ 1.0/\sqrt[3]{D/B} & if \ D/B > 1 \end{cases}$$

$$c = \begin{cases} 1.5 & if \ D/B \leq 1 \\ 1.5(1-\bar{z})^{0.07}(D/B)^{-0.04} & if \ D/B > 1 \end{cases}$$

$$\delta = \begin{cases} 0.4I(H/3)/\sqrt{D/B} & if \ D/B < 1 \\ I(H/3) & if \ D/B = 1 \\ 2(D/B)I(H/3) & if \ D/B > 1 \end{cases}$$

$$I(z) = 0.1\left(z_G / z\right)^{\alpha+0.05}, \ \bar{z} = z/H \tag{14}$$

$$T_1 = 9.4\sqrt{I(H/3)}$$

$$B_1 = \begin{cases} 1.6/\left(1.0+\bar{z}\right) & if \ D/B \leq 1/3 \\ 0.46 & if \ 1/3 < D/B < 1 \\ 0.63\left(4B/H\right) & if \ D/B = 1 \\ 0.63 & if \ D/B > 1 \end{cases}$$

$$B_2 = \begin{cases} 1.6 & if \ D/B \geq 1 \\ 1.6\left(1-\bar{z}\right)^{0.3} & if \ D/B < 1 \end{cases}$$

in which, $S_{ST}(f)$ = effects of the signature turbulence layers
$S_{VS}(f)$ = effects of the vortex shedding
f_S = Strouhal frequency
$I(z)$ = turbulence intensity at height z
z_G = gradient height
α = power law index of vertical profile of mean wind speed

3.2.3 Local torsional moment

The normalized power spectra of local across-wind forces at any level of building are given by following equations:

$$\frac{fS_{FT}(f)}{\sigma_{FT}^2} = B_0 F(f)\frac{fS_{ST}(f)}{\sigma_{ST}^2} + B_1\frac{fS_{VS}(f)}{\sigma_{VS}^2} + B_2\frac{fS_{FP}(f)}{\sigma_{FP}^2}$$

$$\frac{fS_{ST}(f)}{\sigma_{ST}^2} = \frac{\bar{f}_S / k}{\left[1+\xi\left(\bar{f}_S / k\right)^{c1}\right]^{c2}}$$

$$\frac{fS_{VS}(f)}{\sigma_{VS}^2} = \frac{1}{\delta_1\sqrt{2\pi}}\exp\left[-0.5\left(\frac{\ln \bar{f}_s + 0.5\delta_1^{\,2}}{\delta_1}\right)^2\right]$$

$$\frac{fS_{FP}(f)}{\sigma_{FP}^2} = \frac{1}{\delta_2\sqrt{2\pi}}\exp\left[-0.5\left(\frac{\ln \bar{f}_s + 0.5\delta_2^{\,2}}{\delta_2}\right)^2\right]$$

$$\bar{f}_s = f / f_s \,,\; f_s = \frac{0.12 V_H / B}{\left[1+0.38(D/B)^2\right]^{0.89}} \,,\; \xi = 0.62e^{-0.3\bar{z}}$$

$$\bar{f}_m = f / f_m \,,\; f_m = k_m V_H / \sqrt{BD} \,,\; k_m = \begin{cases} 0.25 & if\;\; D/B < 1 \\ 0.30/(D/B)^{0.35} & if\;\; D/B \geq 1 \end{cases}$$

$$F(f) = \left\{1+1.5\sin\left[\pi/(1+(\bar{f}_s/\gamma)^3)\right]\right\}^{-1}$$

$$\delta_2 = 2.5\sqrt{I(H/3)} \;\;,\;\; \delta_1 = \begin{cases} I(H/3) & if\;\; D/B \leq 1 \\ 5I(H/3) & if\;\; D/B > 1 \end{cases}$$

$$k = 1.5 \,,\; I(z) = 0.1(z_G / z)^{\alpha+0.05} \,,\; \bar{z} = z / H$$

$$\gamma = \begin{cases} 1.5 & if\;\; D/B \leq 1 \\ 1.5(D/B) & if\;\; D/B > 1 \end{cases}$$

$$C_2 = 3.75C_1 \;\;,\;\; C_1 = \begin{cases} 1.5 & if\;\; D/B = 1 \\ 1.0 & if\;\; D/B \neq 1 \end{cases}$$

$$B_0 = \begin{cases} 1.2 & if\;\; D/B \leq 1 \\ 0.63 & if\;\; D/B > 1 \end{cases}$$

$$B_1 = \begin{cases} 0.21(1-\bar{z}) + 0.5(D/B) & if\;\; D/B < 1 \\ 0.21(1-\bar{z})/(4B/H) & if\;\; D/B = 1 \\ 0.21(1-\bar{z})(D/B)^{-2} & if\;\; D/B > 1 \end{cases}$$

$$B_2 = \begin{cases} 0.05(1+\bar{z})/(4B/H) & if\;\; D/B = 1 \\ 0.05(1+\bar{z})(D/B) & if\;\; D/B \neq 1 \end{cases} \qquad (15)$$

in which, $S_{ST}(f)$ = effects of the signature turbulence layers

$S_{VS}(f)$ = effects of the vortex shedding

$S_{FP}(f)$ = effects of the flipping phenomenon

f_S = Strouhal frequency

$I(z)$ = turbulence intensity at height z

z_G = gradient height

α = power law index of vertical profile of mean wind speed