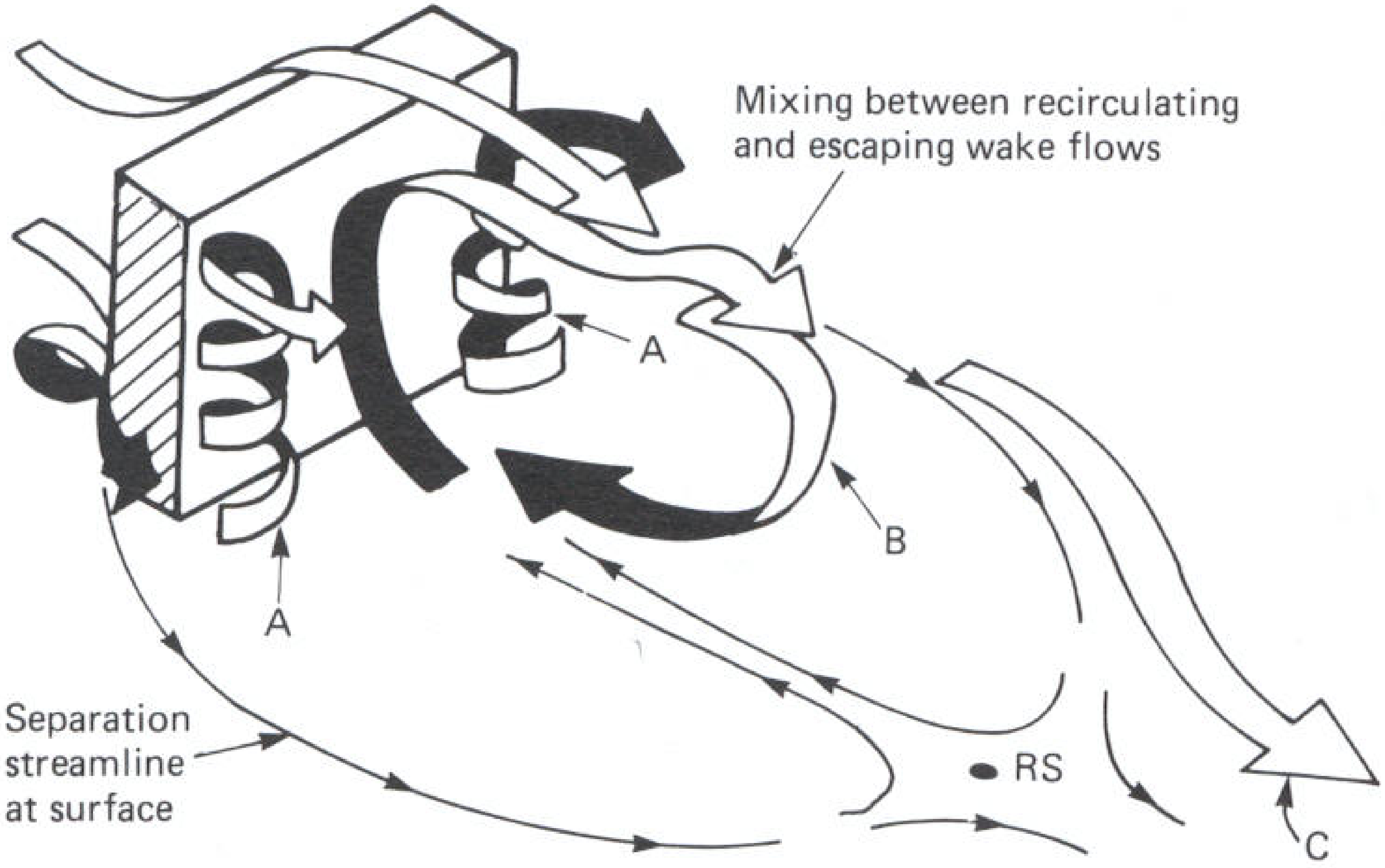
3-D WIND-EXCITED RESPONSE OF THREE-DIMENSIONAL BLUFF-BODIES



3D RESPONSE OF 3D STRUCTURES

Wind tunnel tests

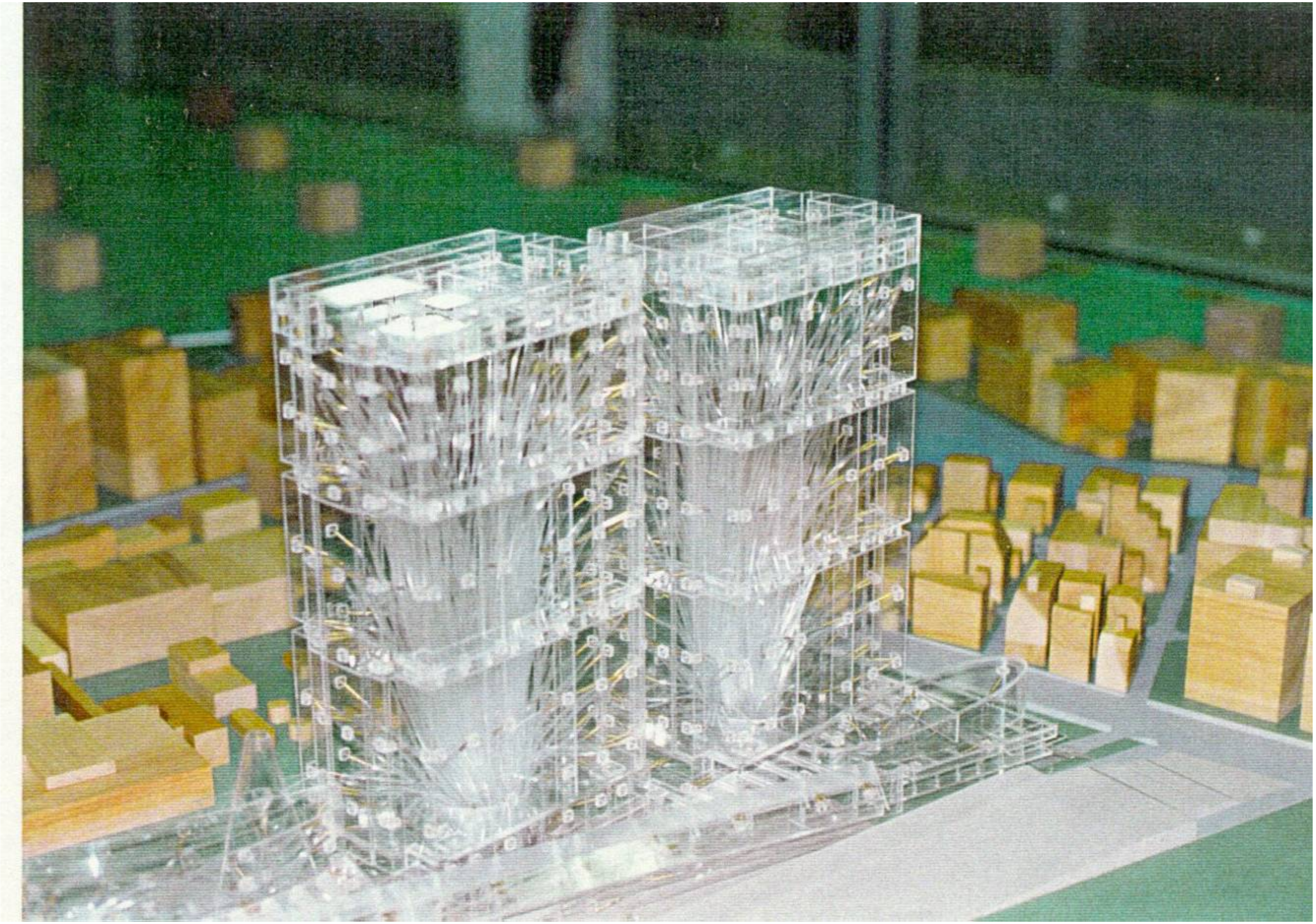
- pressure taps tests
- high-frequency force balance tests
- flexible balance aeroelastic tests
- fully aeroelastic tests

Full-scale tests

CFD analyses

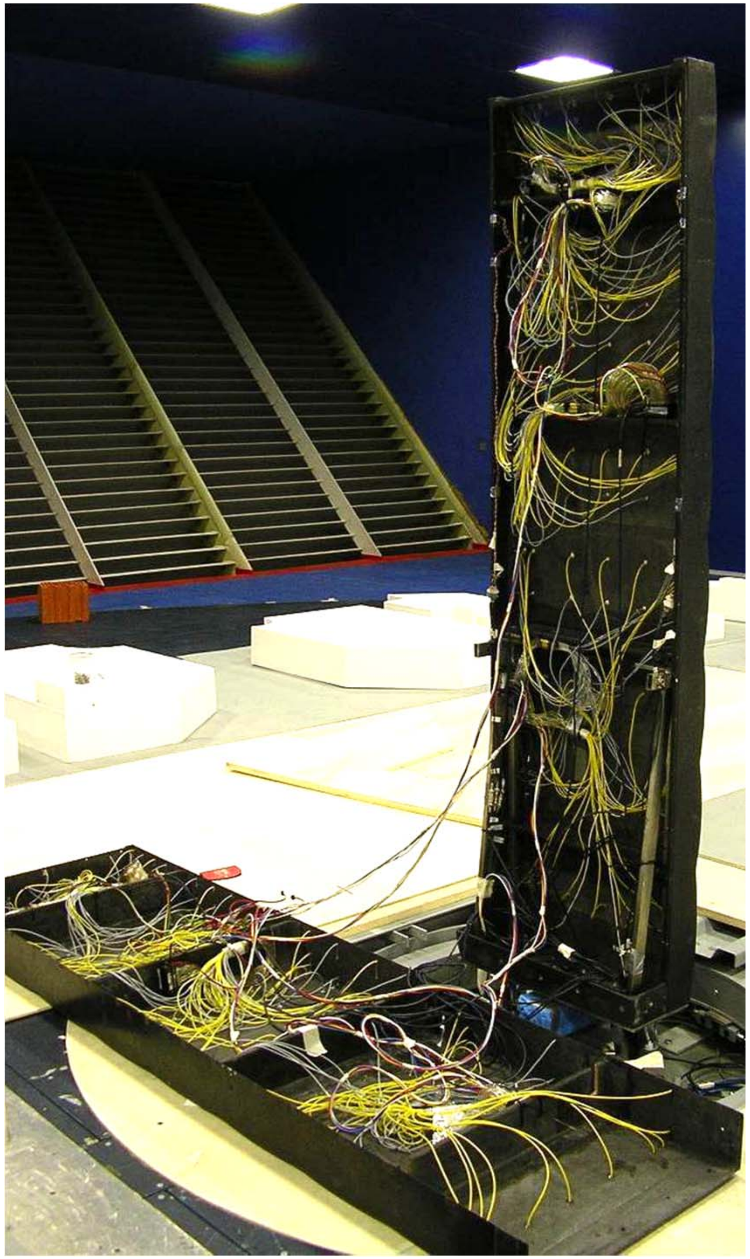
Electronic databases

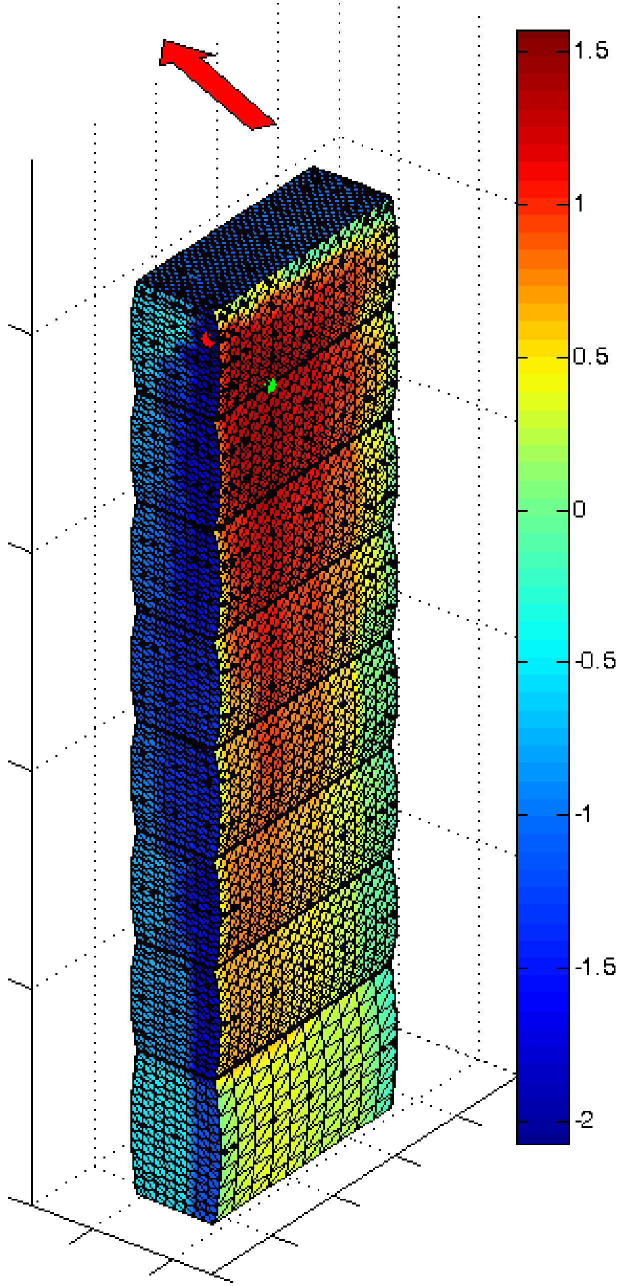
Analytical methods



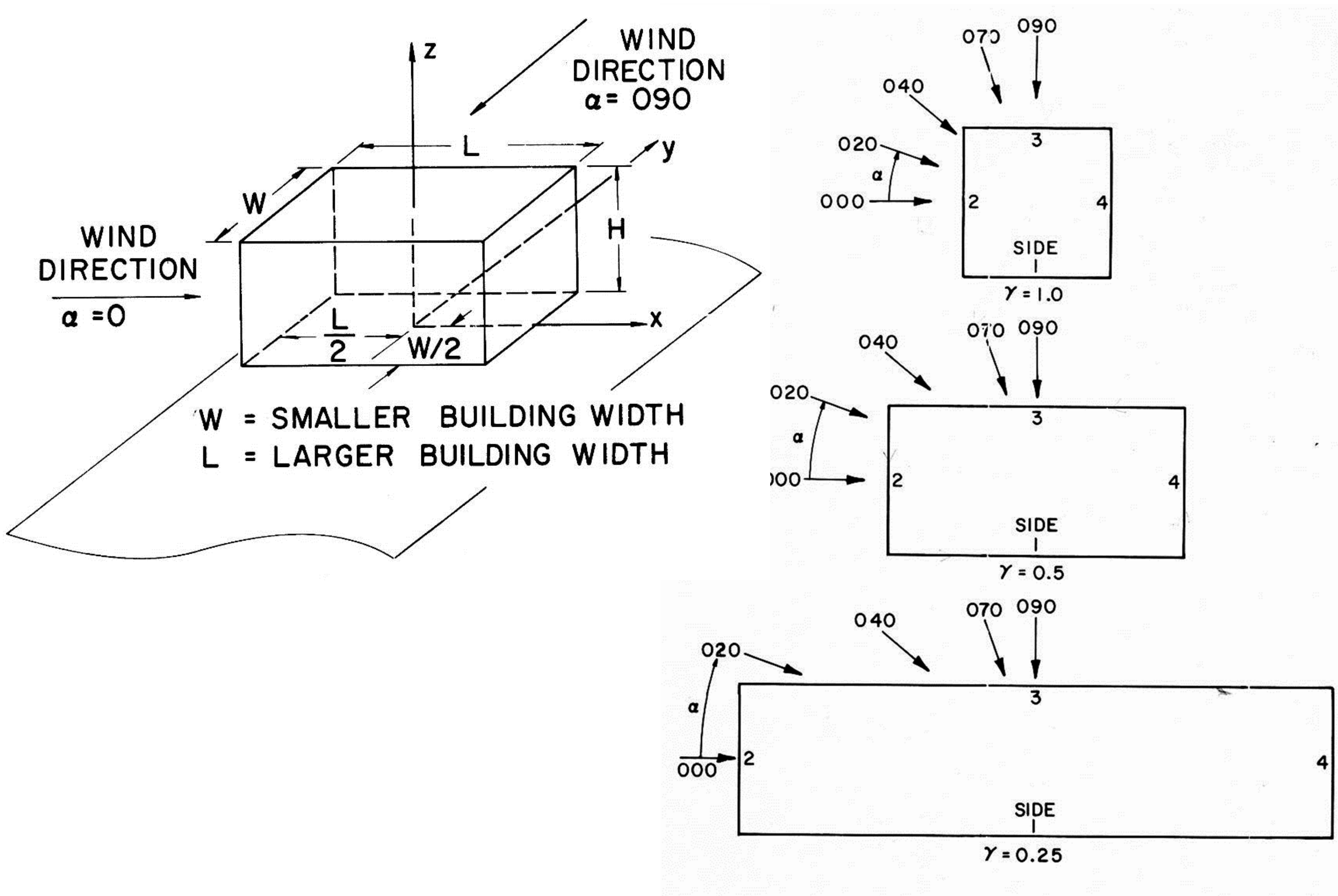
Pressure taps measurements

Pressure taps measurements





Pressure taps measurements



Akins and Paterka (1977)

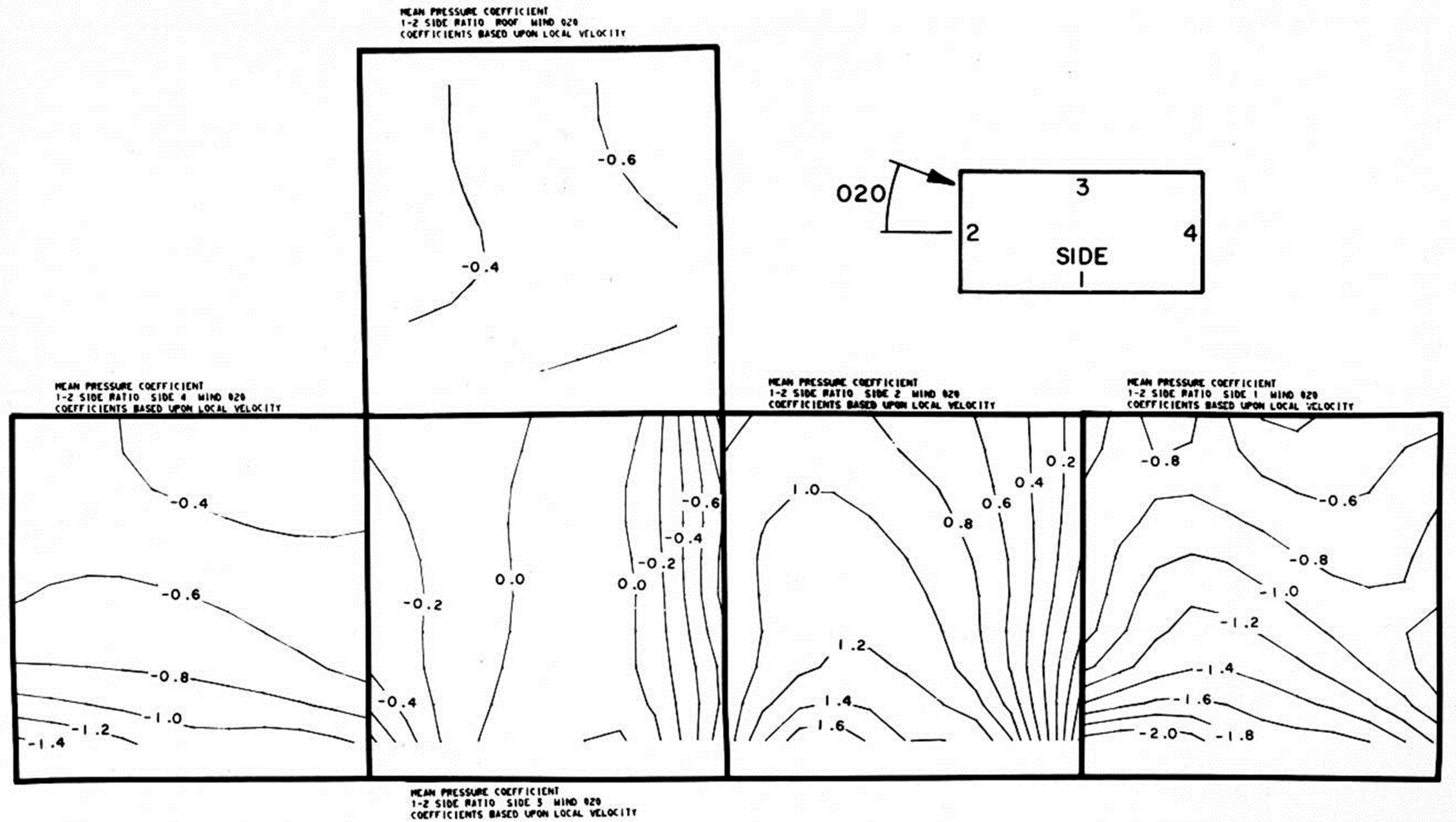
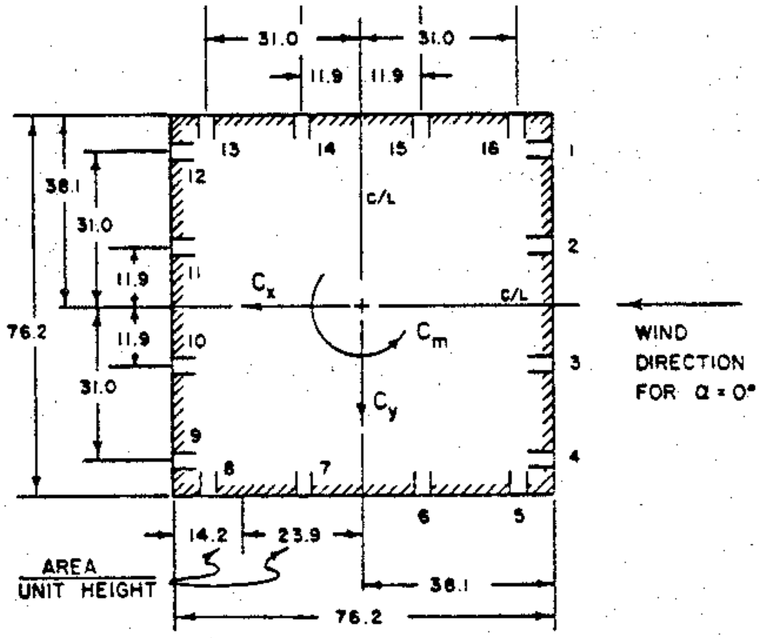
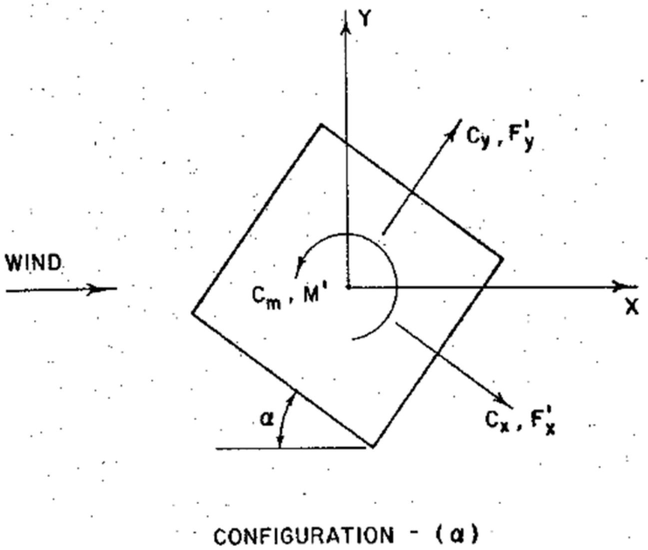
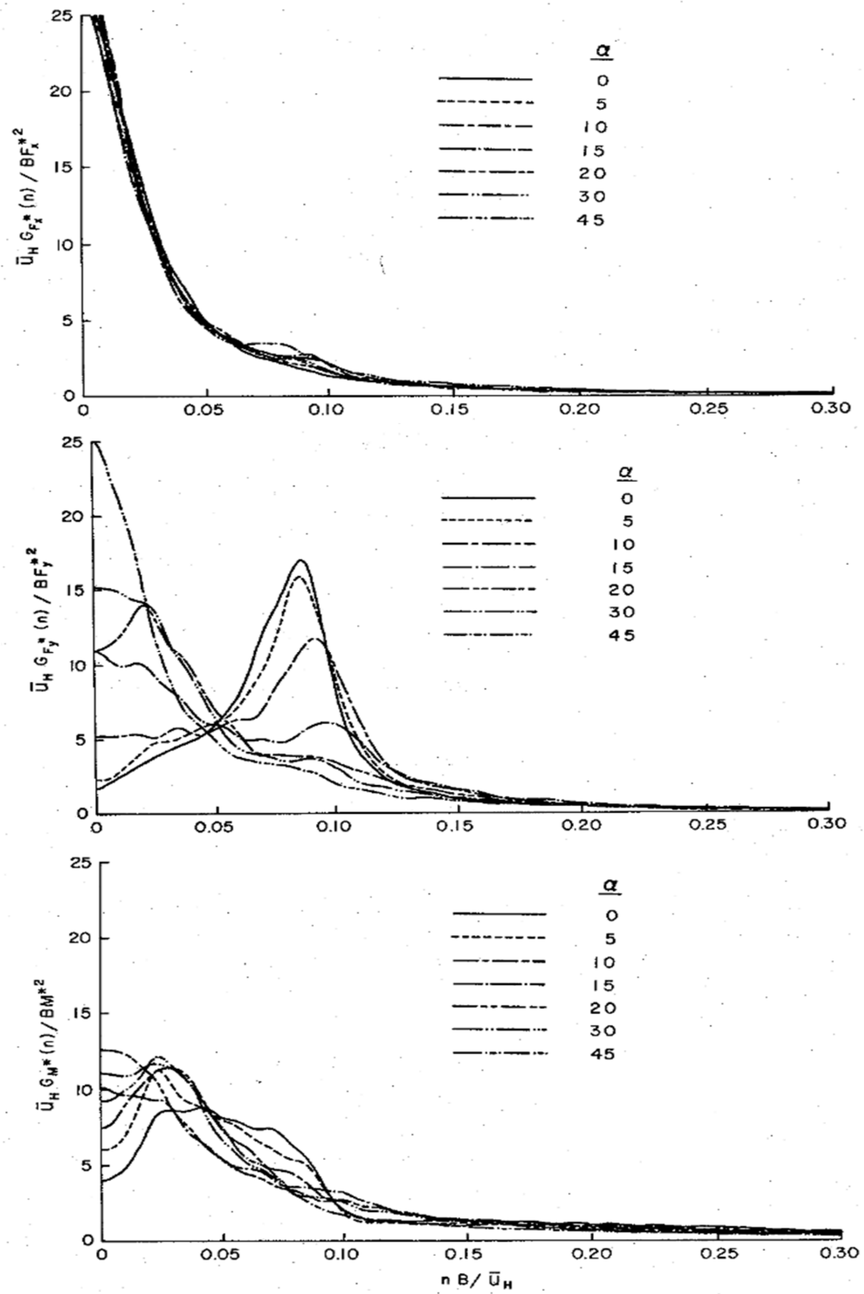


Figure B7. C_{pmean}, $\overline{\beta}$, $\overline{p}$, $\alpha = 20$, $\gamma = 0.5$

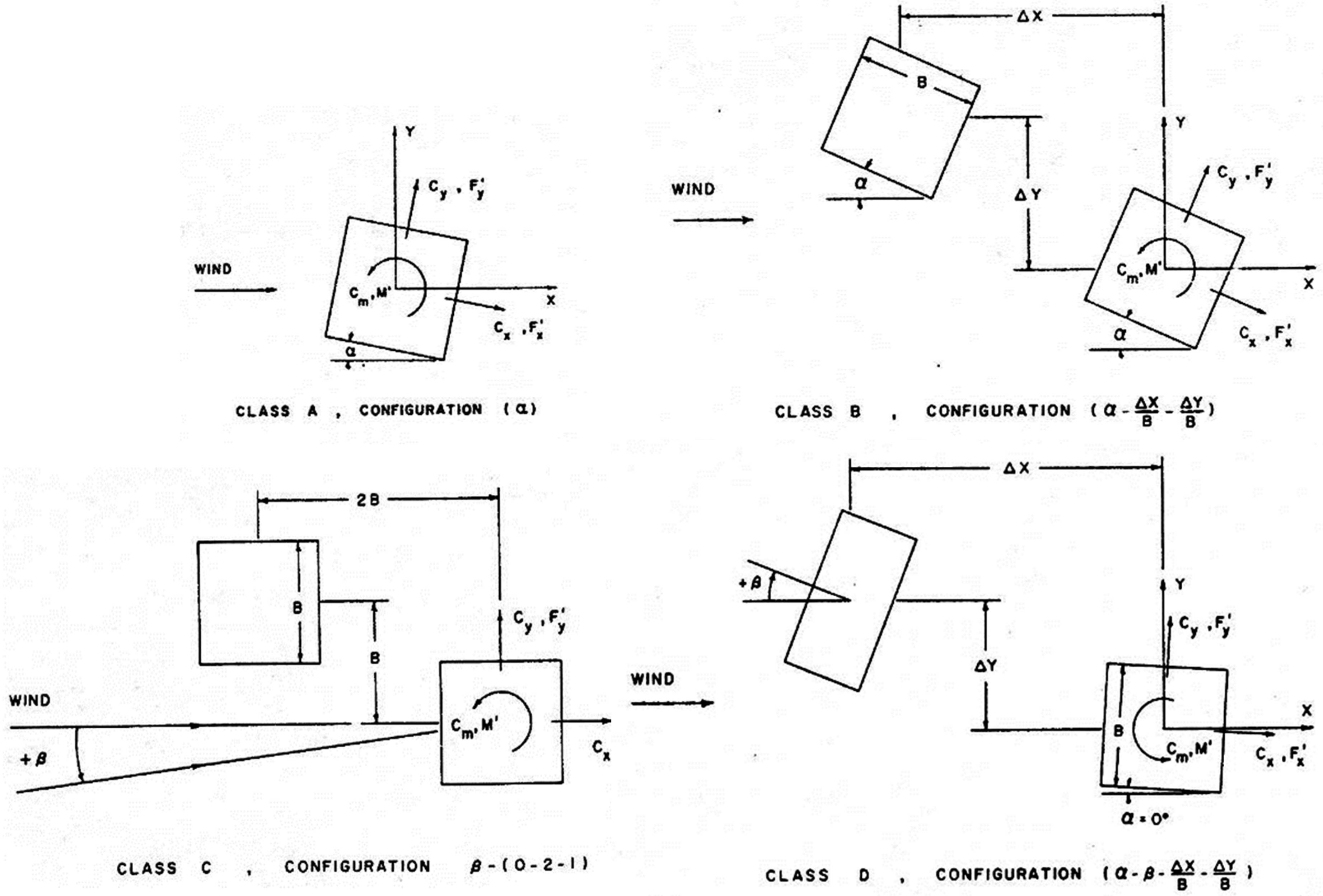
Akins and Paterka (1977)



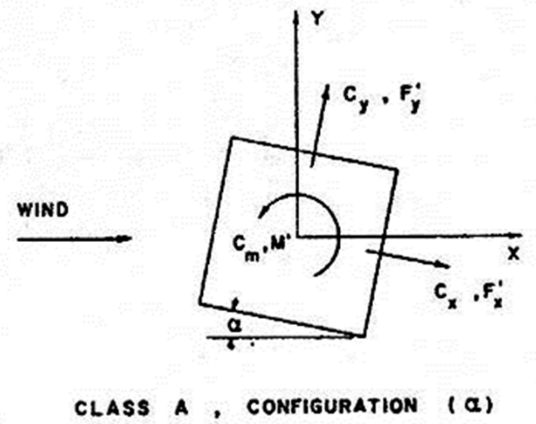


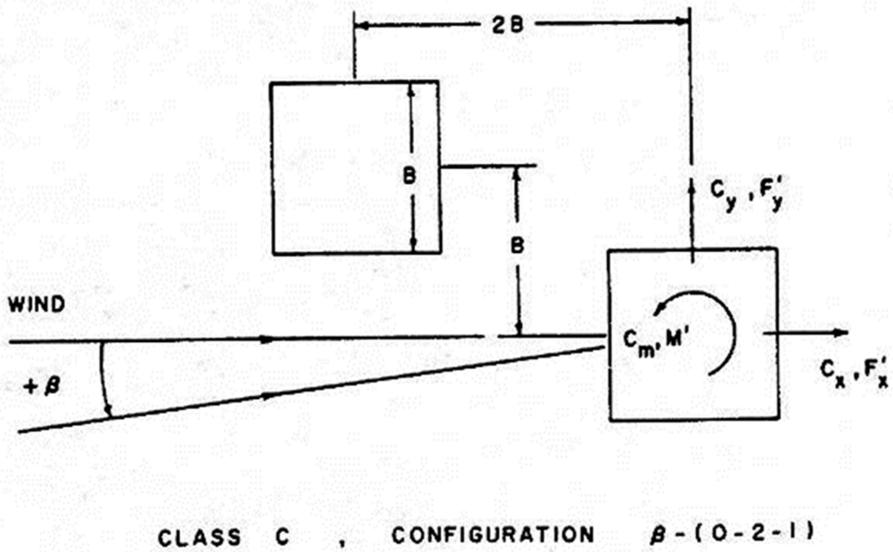


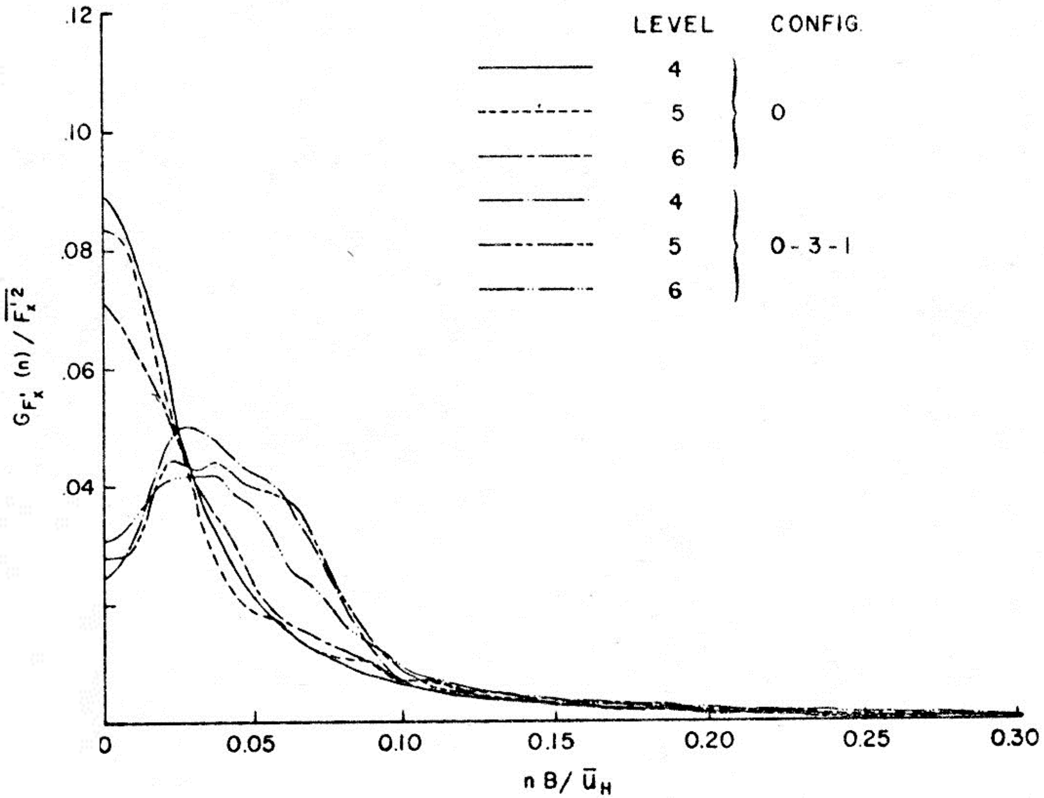
Reinhold and Sparks (1979)



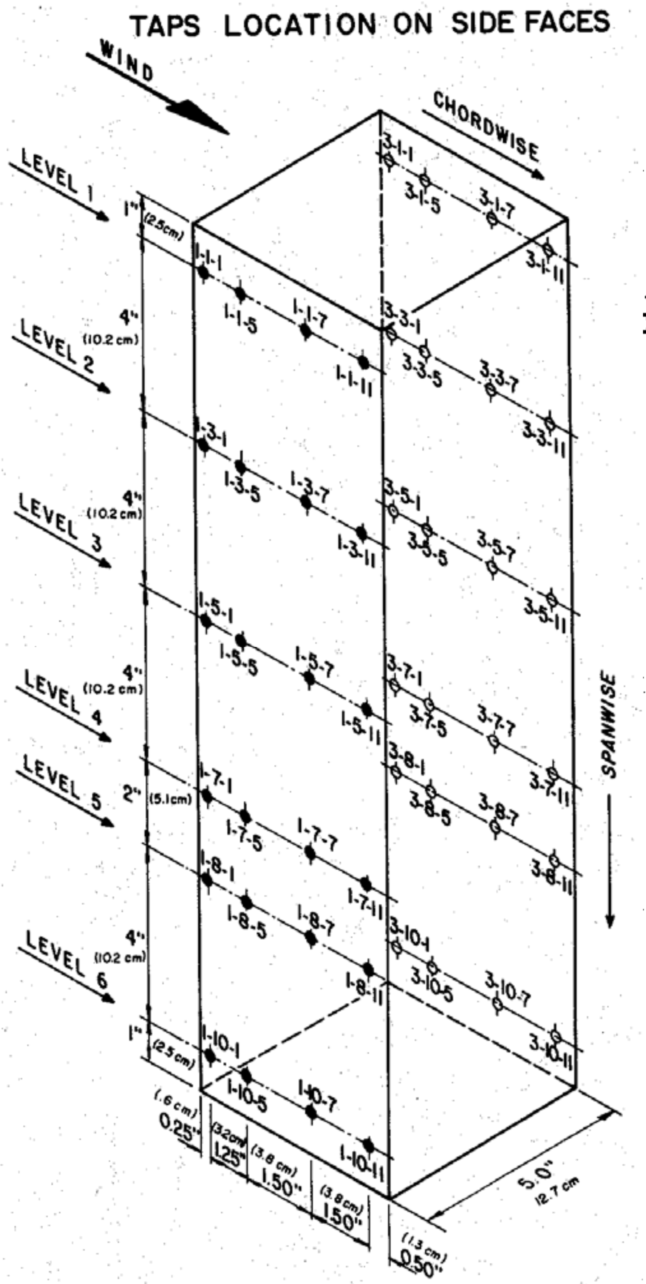
Reinhold and Sparks (1979)

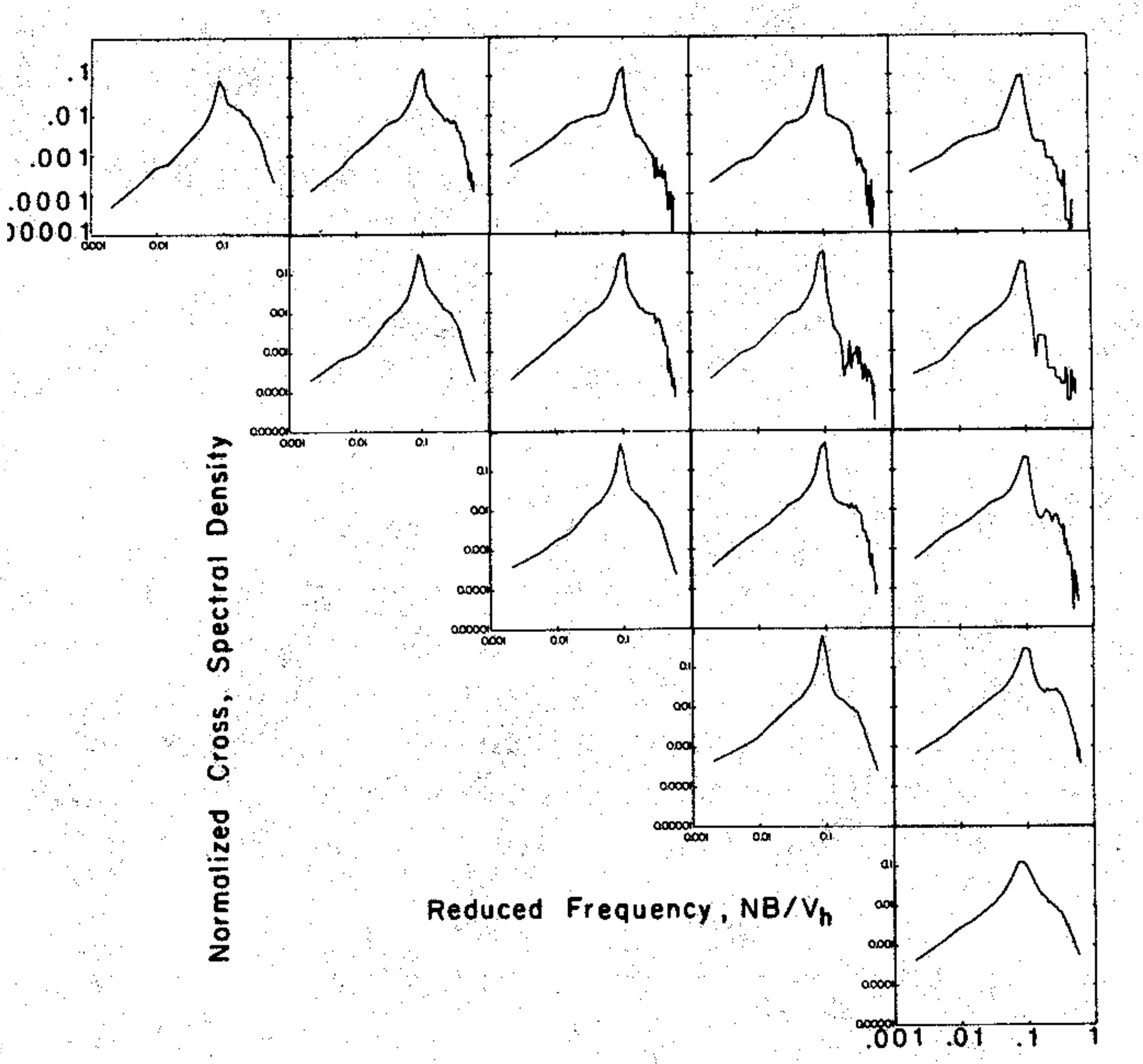




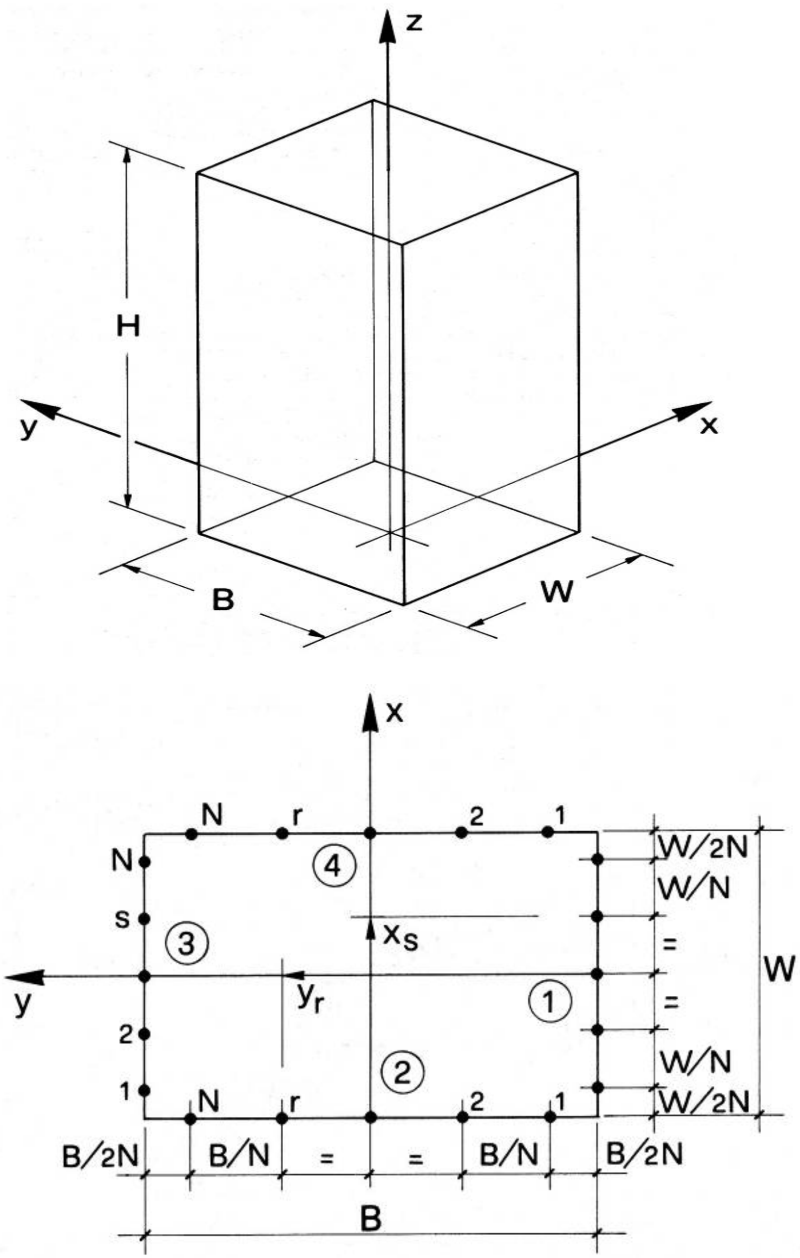


Reinhold and Sparks (1979)

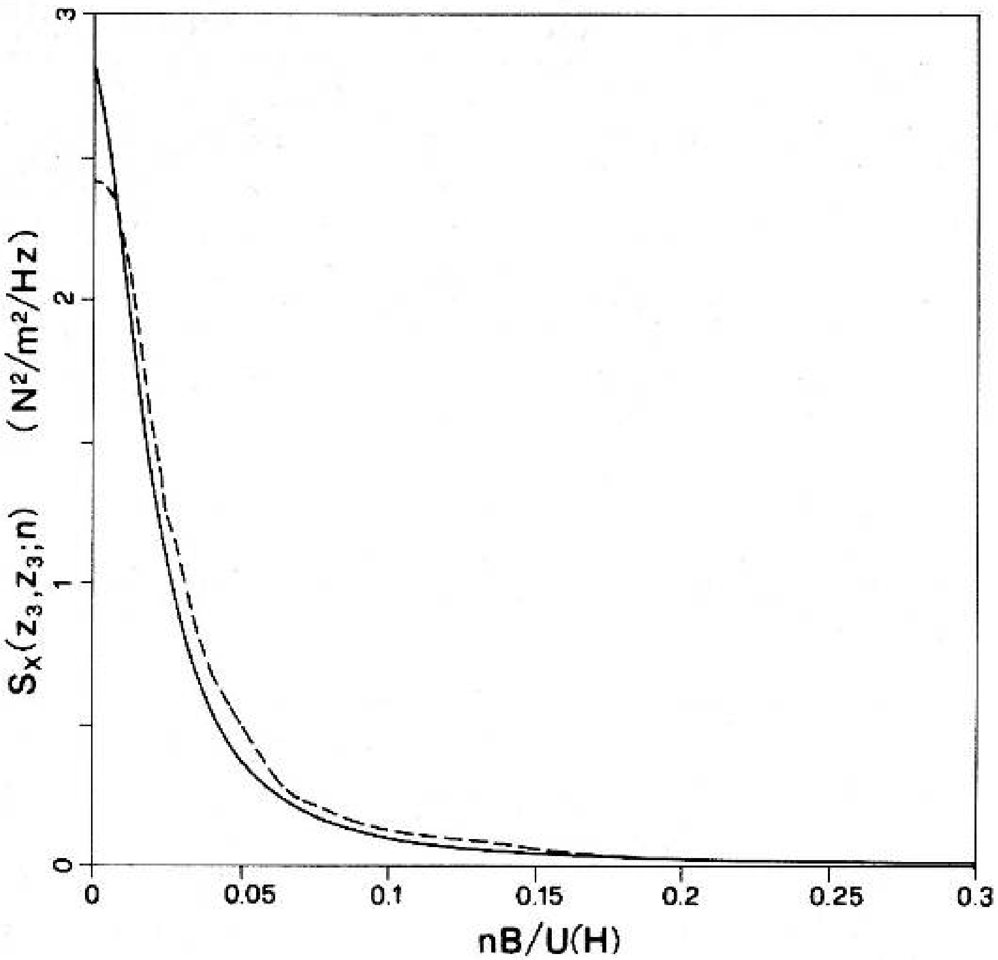

TAPS LOCATION ON SIDE FACES
WIND
CHORDWISE
SPANWISE
LEVEL 1
LEVEL 2
LEVEL 3
LEVEL 4
LEVEL 5
LEVEL 6
1" (2.5cm)
4" (10.2 cm)
4" (10.2 cm)
4" (10.2 cm)
2" (5.1cm)
4" (10.2 cm)
1" (2.5 cm)
(.6 cm) 0.25"
(3.2cm) 1.25"
(3.8 cm) 1.50"
(3.8 cm) 1.50"
(1.3 cm) 0.50"
5.0" 12.7 cm


Normalized Cross, Spectral Density
Reduced Frequency, NB/V_h
.001 .01 .1 1

Kareem (1982)

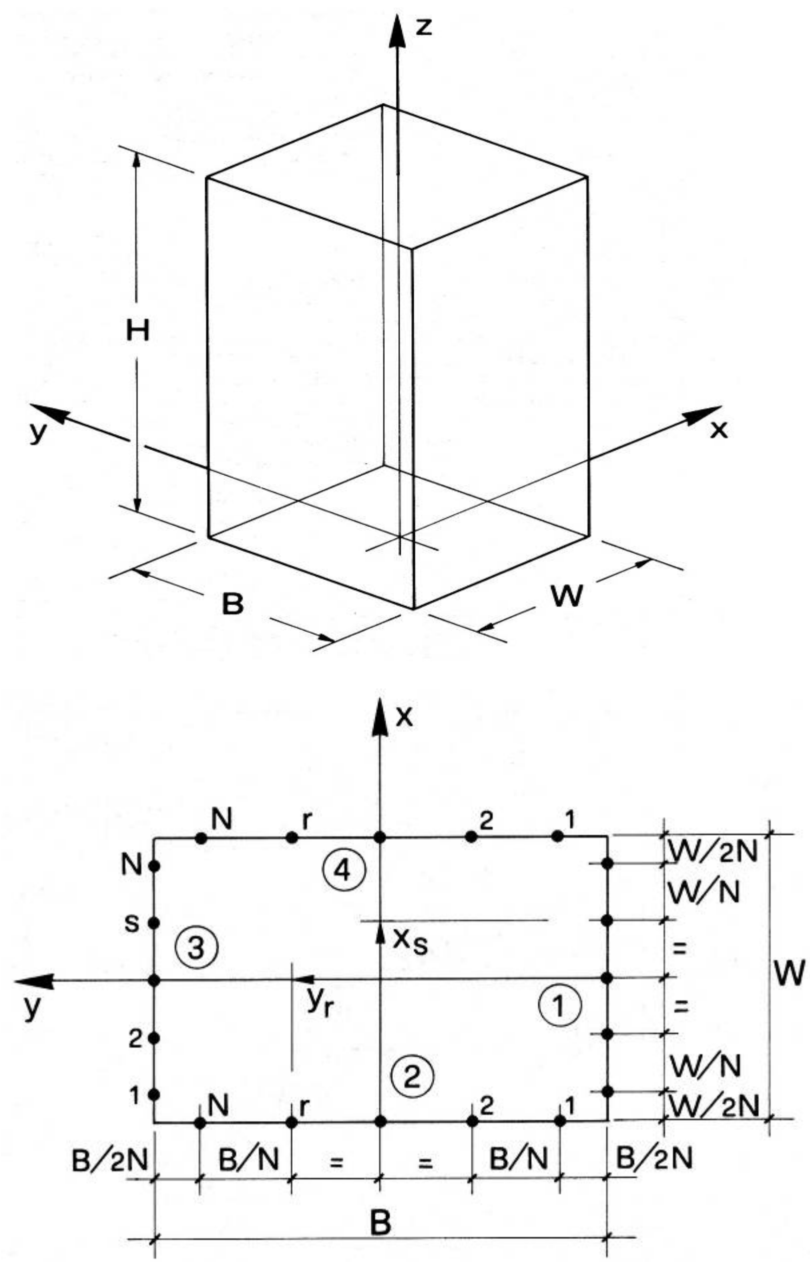


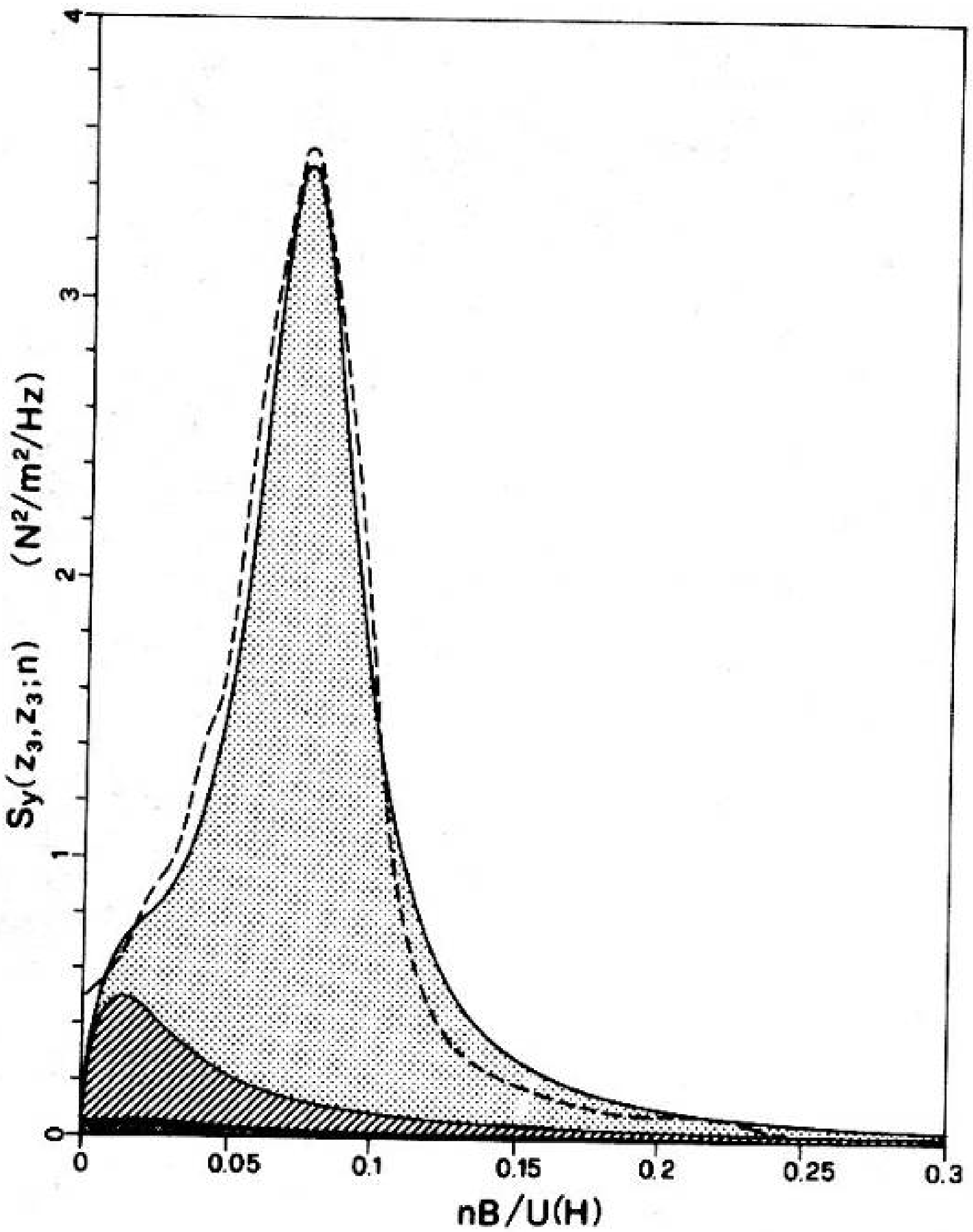
z
H
y
x
B
W
N
r
2
1
s
4
3
xs
yr
W/2N
W/N
=
B/2N
B/N



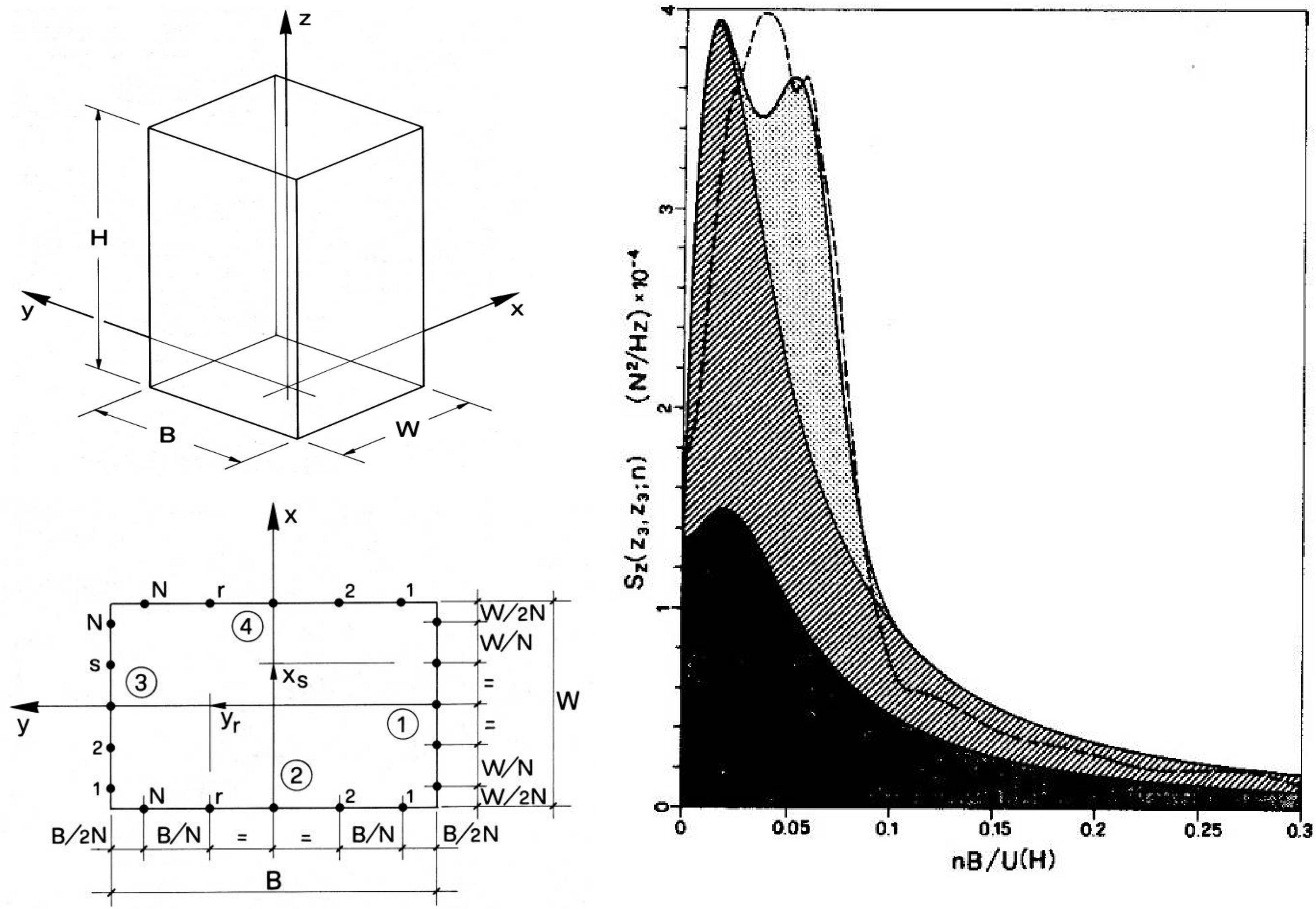
Sx(z3, z3; n) (N²/m²/Hz)
nB/U(H)
0
0.05
0.1
0.15
0.2
0.25
0.3
1
2
3

Solari (1985)

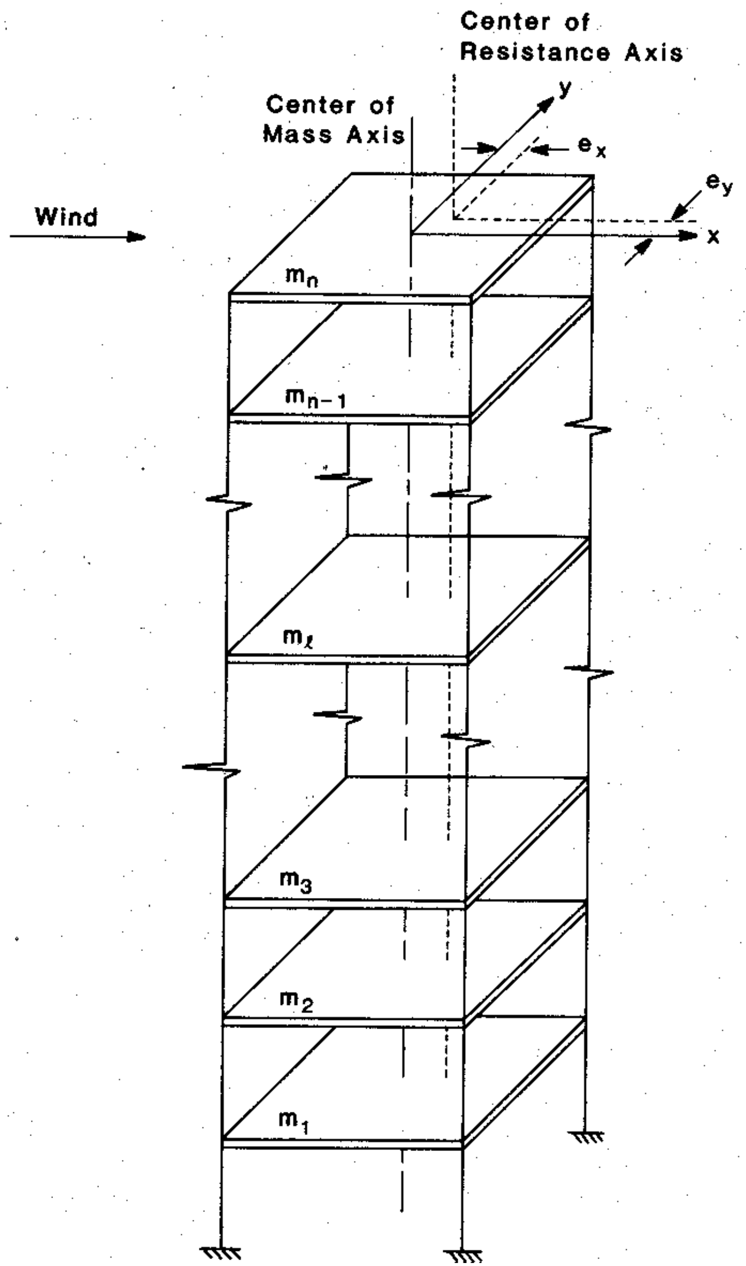

z
H
y
x
B
W
x
N
r
2
1
N
s
4
3
xs
1
y
yr
2
2
1
N
r
2
1
W/2N
W/N
=
=
W/N
W/2N
W
B/2N
B/N
=
=
B/N
B/2N
B


Sy(z3, z3; n) (N²/m²/Hz)
0
1
2
3
4
0
0.05
0.1
0.15
0.2
0.25
0.3
nB/U(H)

Solari (1985)


z
H
y
x
B
W
N
r
2
1
s
④
③
②
①
x_s
y_r
W/2N
W/N
=
B/2N
B/N
$S_z(z_3, z_3; n)$ $(N^2/Hz) \times 10^{-4}$
nB/U(H)
0
1
2
3
4
0.05
0.1
0.15
0.2
0.25
0.3

Solari (1985)



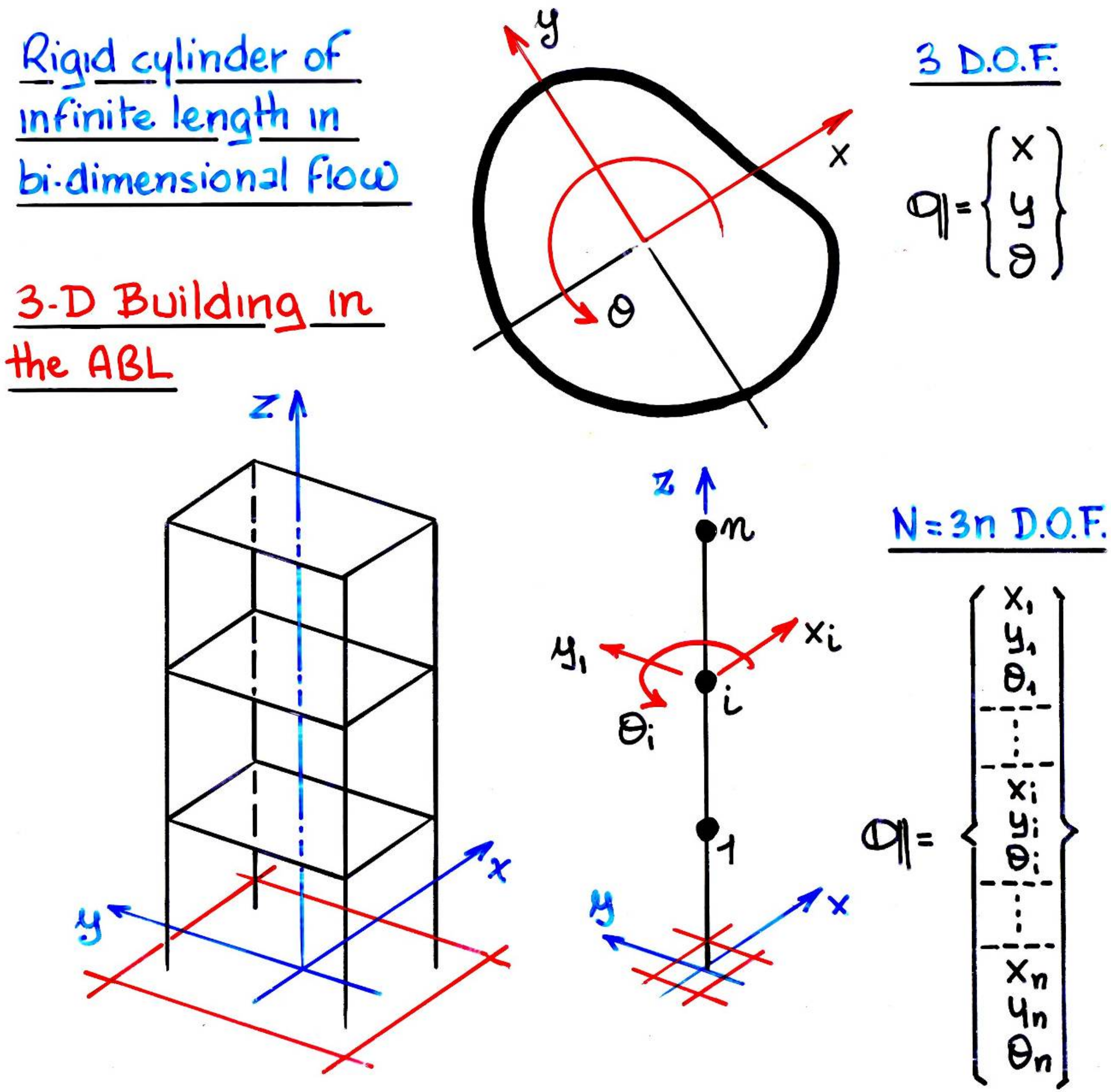
Time Domain Solutions

Patrickson & Friedman (1979)
Yang, Liu, Samali (1981)
Torkomani & Pramono (1985)

Frequency Domain Solutions

Sidarous & Vanderbilt (1979)
Foutch & Safak (1981, 1987)
Kareem (1981, 1985)
Reinhold (1983)
Tallin & Ellingwood (1984)
Solari (1986)

3D wind-excited response



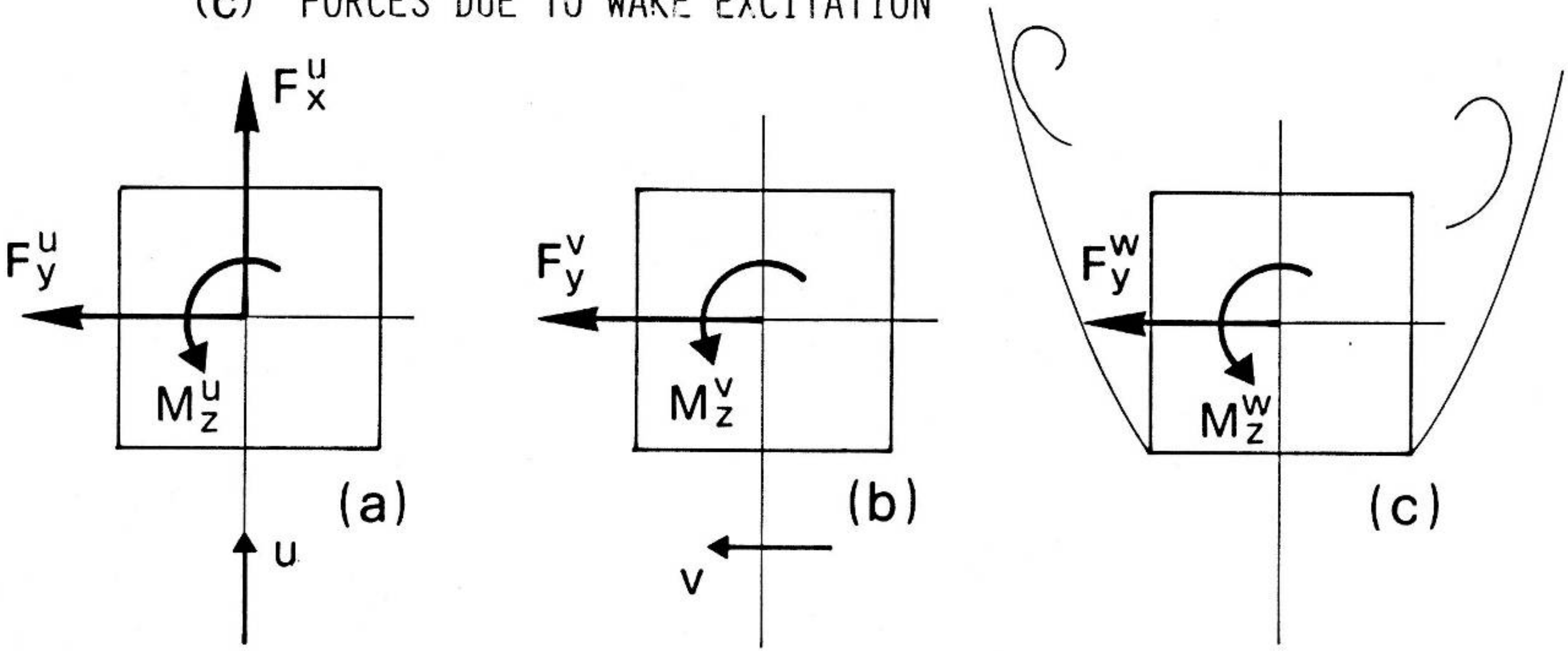
Computer program WL3D - Solari (1986)

FLUCTUATING WIND LOADS ARE CONSIDERED TO BE THE SUM OF THREE MAIN CONTRIBUTIONS ASSUMED AS STATISTICALLY INDEPENDENT:

(a) FORCES DUE TO ALONG-WIND TURBULENCE;

(b) FORCES DUE TO ACROSS-WIND TURBULENCE;

(c) FORCES DUE TO WAKE EXCITATION



Computer program WL3D - Solari (1986)

BUILDINGS SELECTED AS TEST CASES

DESCRIPTION	UNITS	BUILDING 1	BUILDING 2
HEIGHT OF BUILDING (H)	M	200	300
WIDTH OF BUILDING (B)	M	50	50
DEPTH OF BUILDING (W)	M	50	50
MASS PER UNIT LENGTH	KG/M	500 000	500 000
POLAR MASS MOMENT OF INERTIA PER UNIT LENGTH	KG M	22 500 000	22 500 000
ALONG-WIND NATURAL FREQUENCY	Hz	0.2	0.1
ACROSS-WIND NATURAL FREQUENCY	Hz	0.2	0.1
TORSIONAL NATURAL FREQUENCY	Hz	0.25	0.125
DAMPING RATIO	%	1	1

GEOMETRIC, ELASTIC AND MASS CENTRES OF BUILDINGS ARE ASSUMED AS COINCIDENT

Computer program WL3D - Solari (1986)

STANDARD DEVIATIONS OF TOP FLOOR DISPLACEMENTS (M,RAD)

	BUILDING 1			BUILDING 2		
	$\sigma_{xo}^{(0)}$	$\sigma_{yo}^{(0)}$	$\sigma_{\vartheta o}^{(0)}$	$\sigma_{xo}^{(0)}$	$\sigma_{yo}^{(0)}$	$\sigma_{\vartheta o}^{(0)}$
u	0.029	0.019	0.00049	0.170	0.091	0.0024
u + v	0.029	0.049	0.00091	0.170	0.250	0.0047
u + v + w	0.029	0.073	0.00093	0.170	0.718	0.0048

STANDARD DEVIATIONS OF TOP FLOOR ACCELERATIONS (M/S^2, RAD/S^2)

	BUILDING 1			BUILDING 2		
	$\sigma_{xo}^{(2)}$	$\sigma_{yo}^{(2)}$	$\sigma_{\vartheta o}^{(2)}$	$\sigma_{xo}^{(2)}$	$\sigma_{yo}^{(2)}$	$\sigma_{\vartheta o}^{(2)}$
u	0.036	0.028	0.00110	0.061	0.035	0.00140
u + v	0.036	0.074	0.00210	0.061	0.096	0.00280
u + v + w	0.036	0.102	0.00210	0.061	0.273	0.00280

Computer program WL3D - Solari (1986)

RATIOS BETWEEN CORNER (C) AND CENTRE (O) DISPLACEMENT STANDARD DEVIATIONS

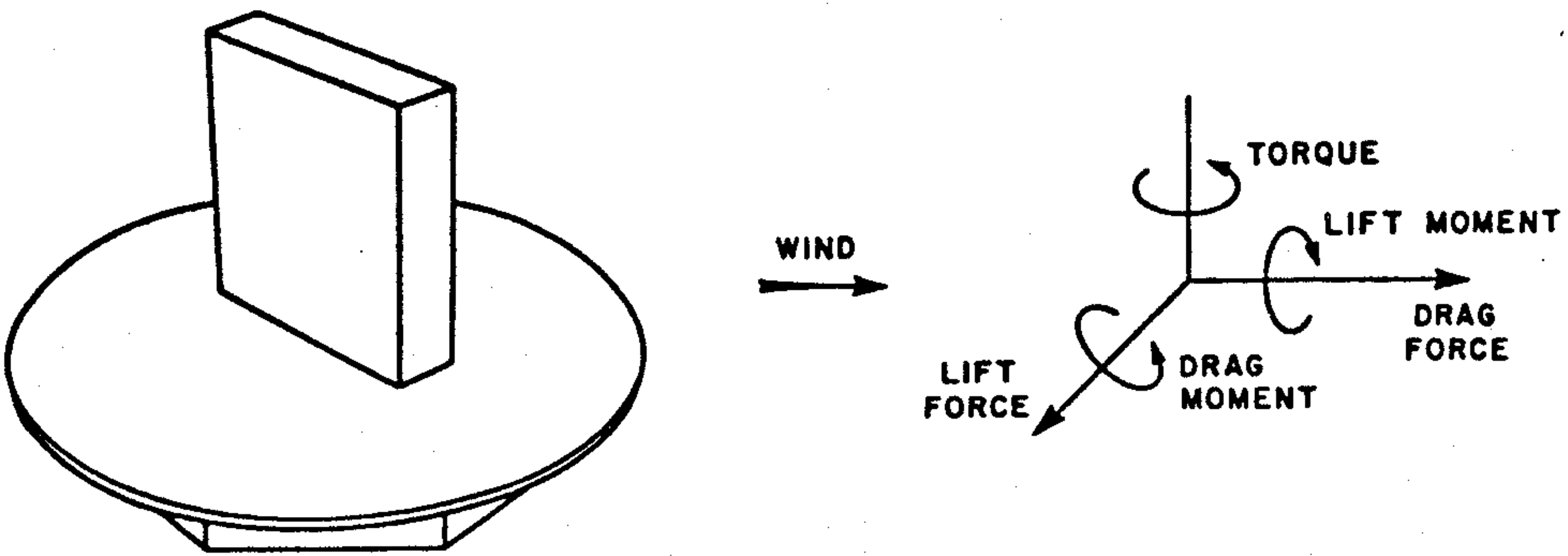
	BUILDING 1		BUILDING 2	
	$\sigma_{xc}^{(0)}/\sigma_{xo}^{(0)}$	$\sigma_{yc}^{(0)}/\sigma_{yo}^{(0)}$	$\sigma_{xc}^{(0)}/\sigma_{xo}^{(0)}$	$\sigma_{yc}^{(0)}/\sigma_{yo}^{(0)}$
u	1.08	1.19	1.06	1.20
u + v	1.27	1.12	1.22	1.11
u + v + w	1.28	1.07	1.23	1.02

RATIOS BETWEEN CORNER (C) AND CENTRE (O) ACCELERATION STANDARD DEVIATIONS

	BUILDING 1		BUILDING 2	
	$\sigma_{xc}^{(2)}/\sigma_{xo}^{(2)}$	$\sigma_{yc}^{(2)}/\sigma_{yo}^{(2)}$	$\sigma_{xc}^{(2)}/\sigma_{xo}^{(2)}$	$\sigma_{yc}^{(2)}/\sigma_{yo}^{(2)}$
u	1.27	1.44	1.16	1.45
u + v	1.77	1.24	1.53	1.25
u + v + w	1.77	1.13	1.53	1.04

Computer program WL3D - Solari (1986)

High-frequency force balance measurements



Base overturning moment

$$M(t) = \int_0^H f(z,t)\, z\, dz$$

$$\bar{M} = \int_0^H \bar{f}(z)\, z\, dz$$

$$S_M(n) = \int_0^H \int_0^H S_f(z,z';n)\, z\, z'\, dz\, dz'$$

coincides with the modal force for a linear mode shape

Davenport and Tschanz (1981, 1983)

High-Frequency force-balance wind-tunnel tests

$$\bar{C}_M = \frac{2\bar{M}}{\varrho \bar{u}^2 B H^2}\ ; \quad \tilde{C}_M = \frac{2\sigma_M}{\varrho \bar{u}^2 B H^2}\ ; \quad \frac{n S_M(n)}{\sigma_M^2} = f\left(\frac{nB}{\bar{u}}\right)$$

Alongwind response • linear mode shape $\psi_1(z) = z$

$$X(z;t) = z \cdot p_1(t)\ ; \quad p_1(t) = \bar{p}_1 + p_1'(t)$$

$$\bar{p}_1 = \frac{\bar{F}_1}{m_1 (2\pi n_1)^2}\ ; \quad m_1 = \int_0^H \mu(z) z^2 dz$$

$$\bar{F}_1 = \int_0^H \bar{F}(z) z dz = \bar{M} = \frac{1}{2} \varrho \bar{u}^2 B H^2 \bar{C}_M$$

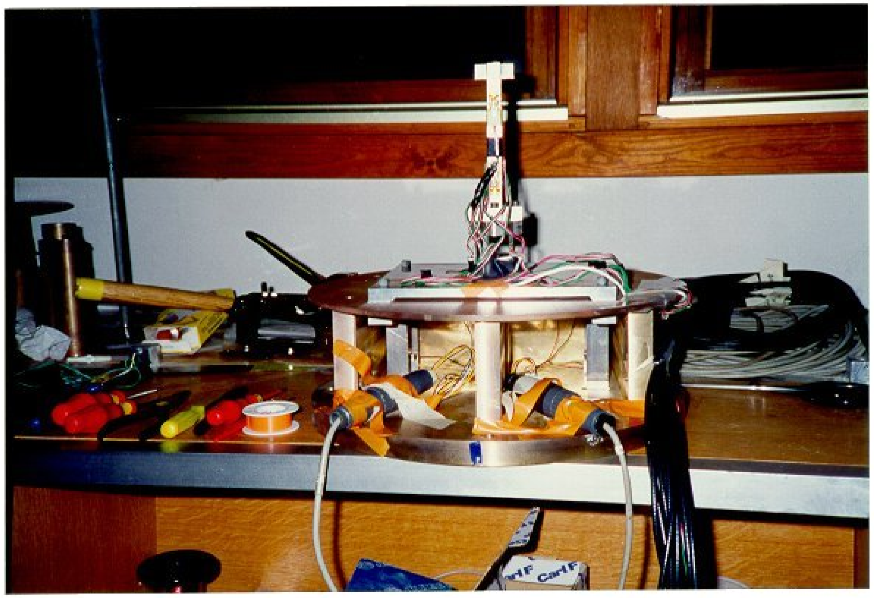
$$\sigma_{p_1}^2 = \sigma_{Qp_1}^2 + \sigma_{Dp_1}^2$$

$$\sigma_{Qp_1}^2 = \frac{\sigma_{F_1}^2}{m_1^2 (2\pi n_1)^4}\ ; \quad \sigma_{F_1} = \sigma_M = \frac{1}{2} \varrho \bar{u}^2 B H^2 \tilde{C}_M$$

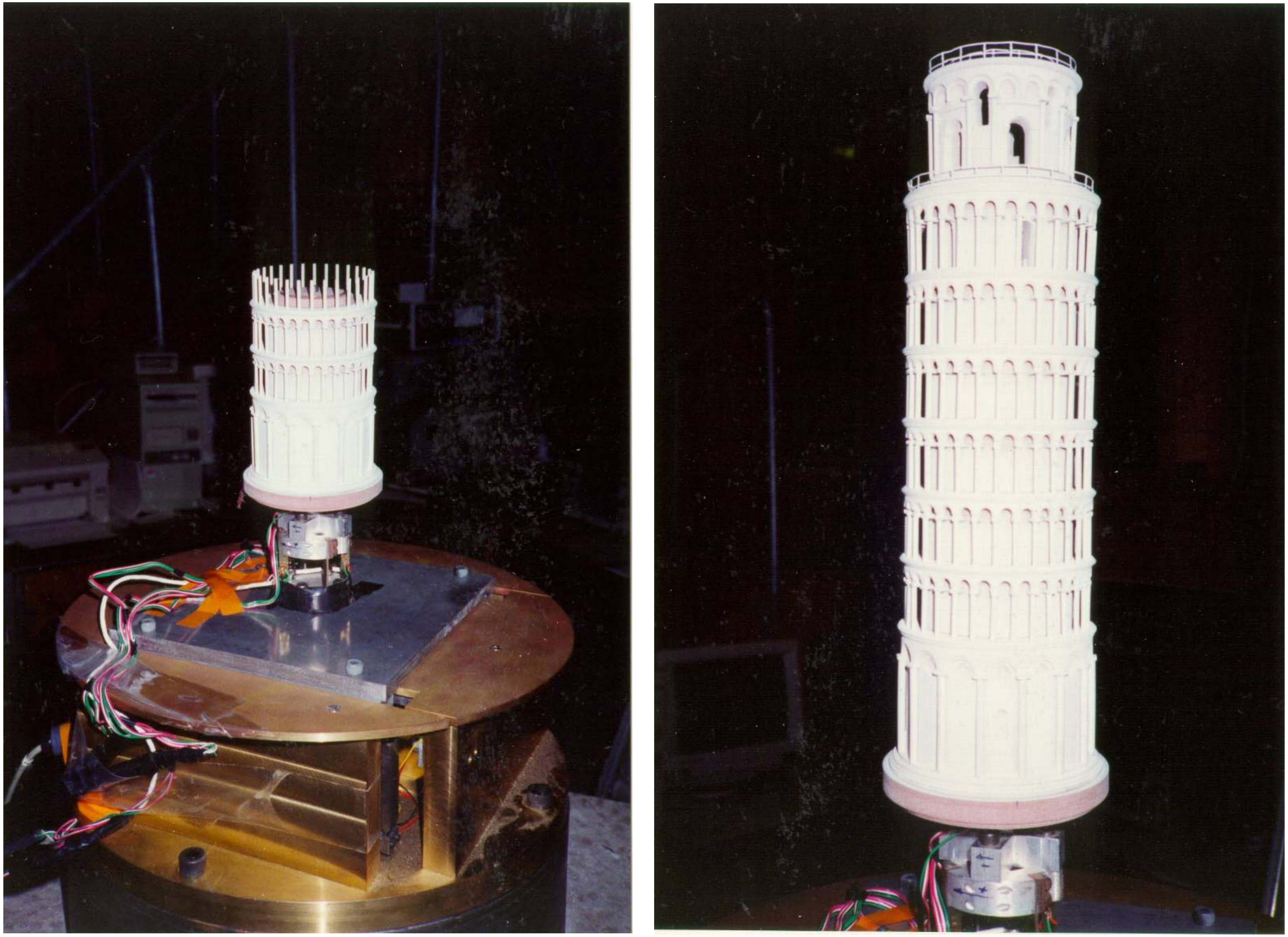
$$\sigma_{Dp_1}^2 = \frac{1}{m_1^2 (2\pi n_1)^4} \frac{\pi n_1}{4\xi} S_{F_1}(n_1)$$

$$S_{F_1}(n) = \int_0^H \int_0^H S_{F'F'}(z,z';n) z z' dz dz' = S_M(n) = \frac{\sigma_M^2}{n} f\left(\frac{nB}{\bar{u}}\right)$$

High-frequency force balance tests on the Leaning Tower of Pisa

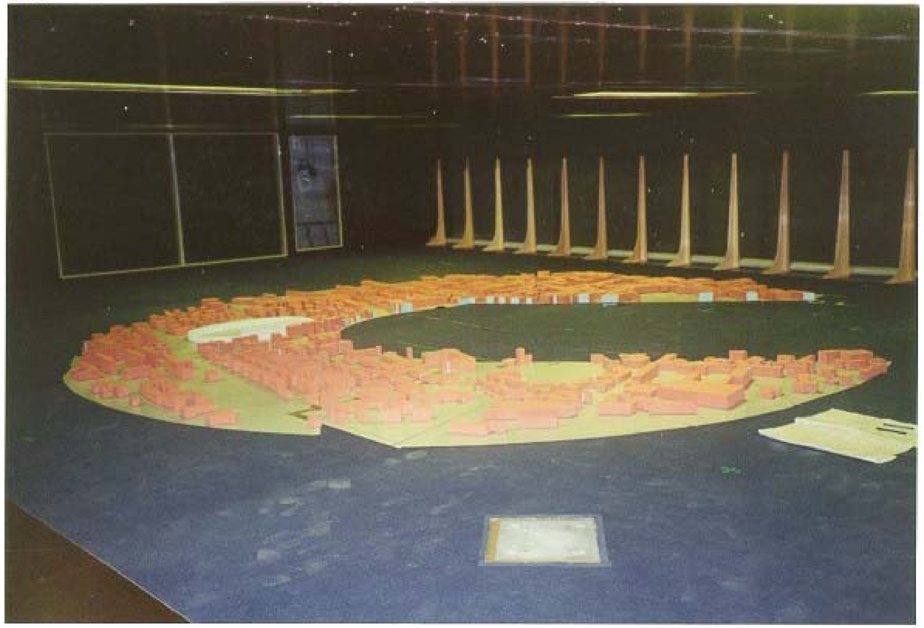
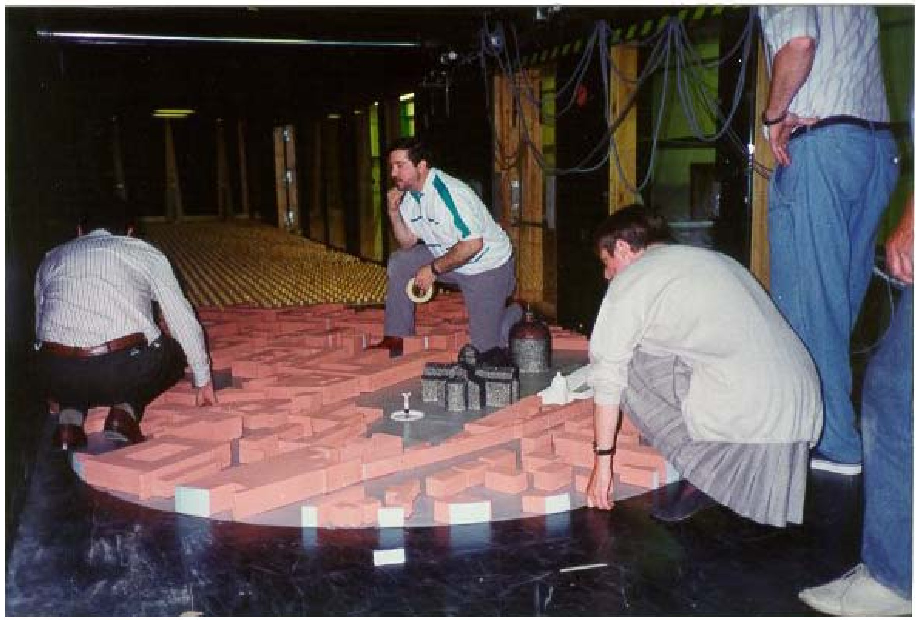


High-frequency force balance tests on the Leaning Tower of Pisa



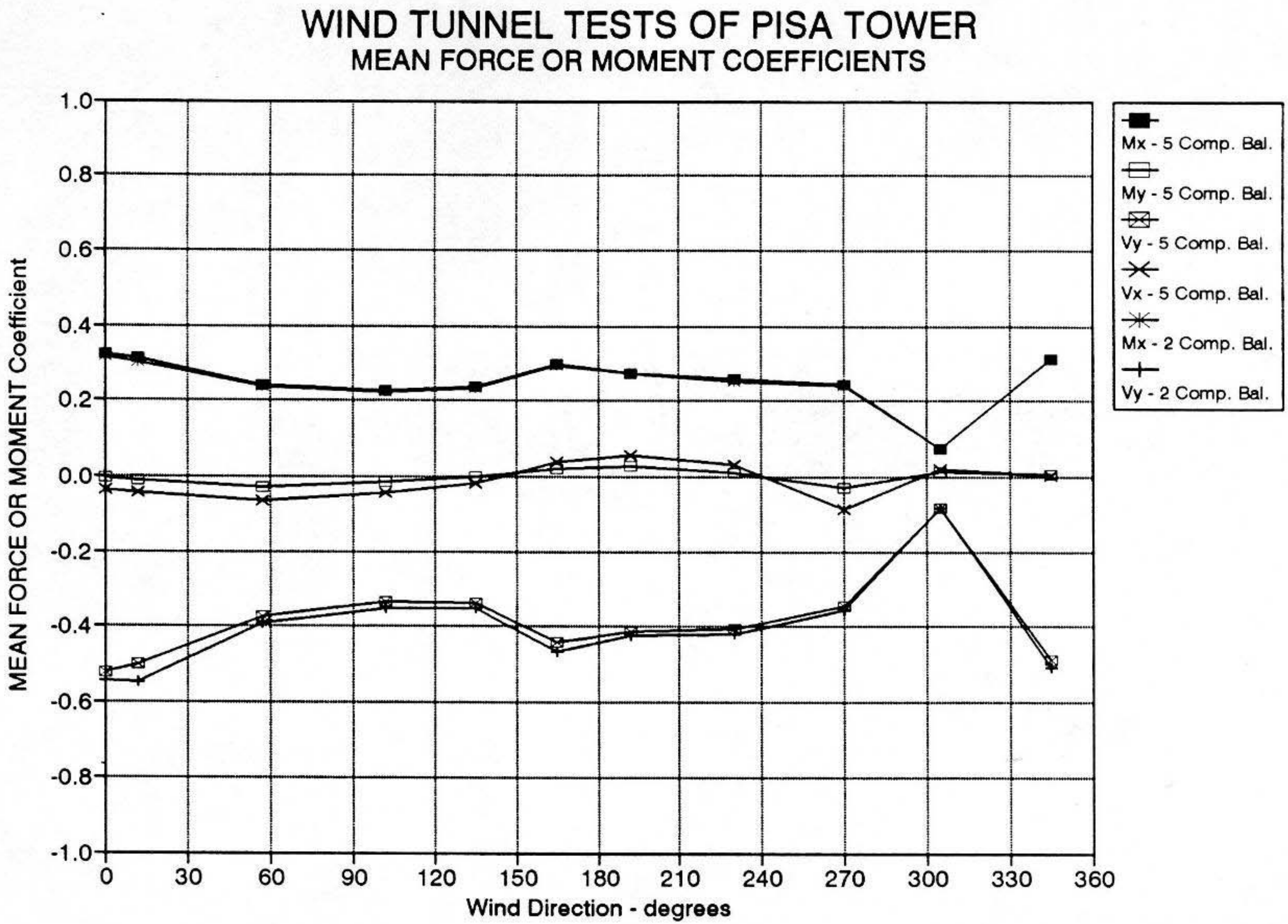
High-frequency force balance tests on the Leaning Tower of Pisa

High-frequency force balance tests on the Leaning Tower of Pisa

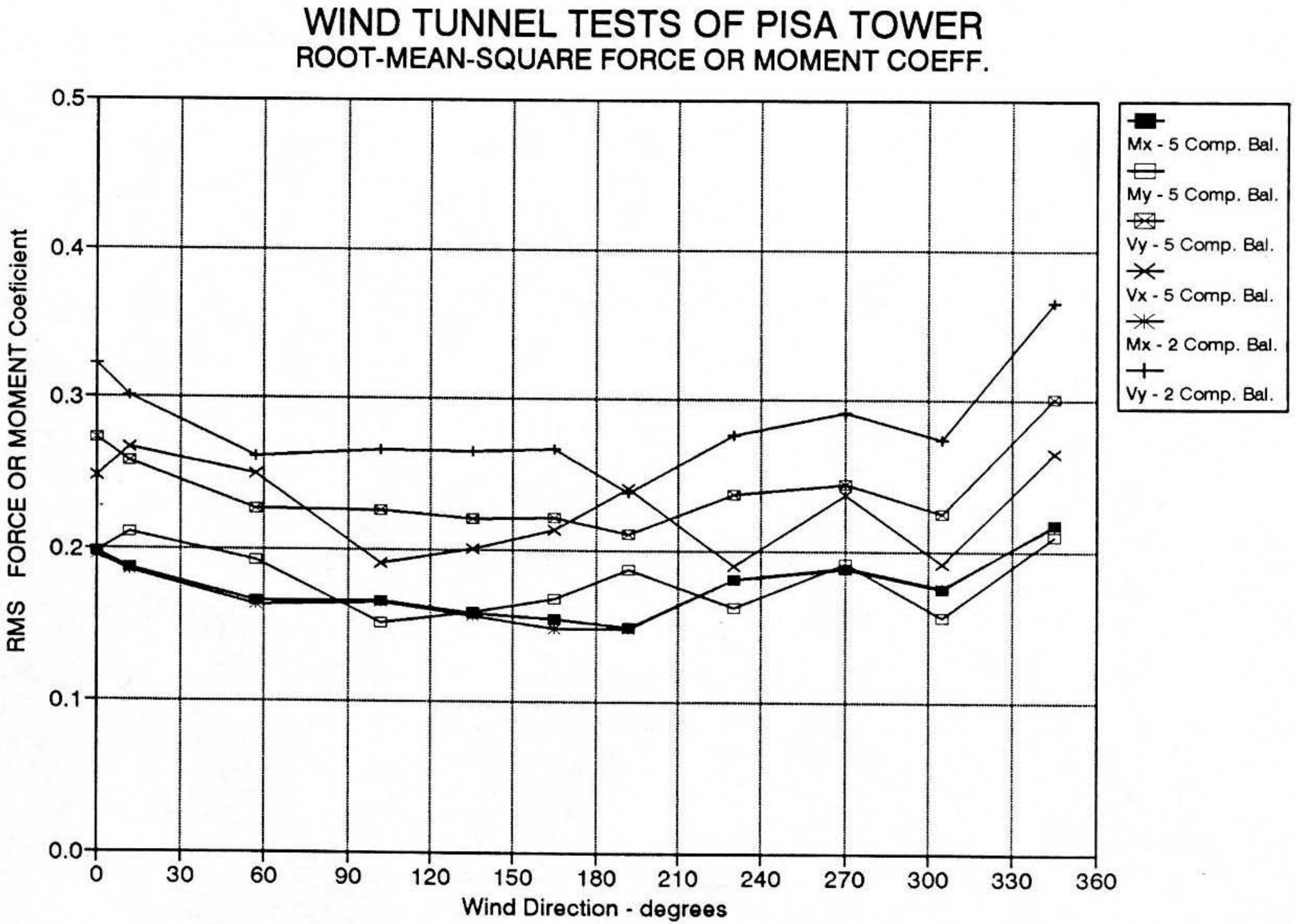




High-frequency force balance tests on the Leaning Tower of Pisa

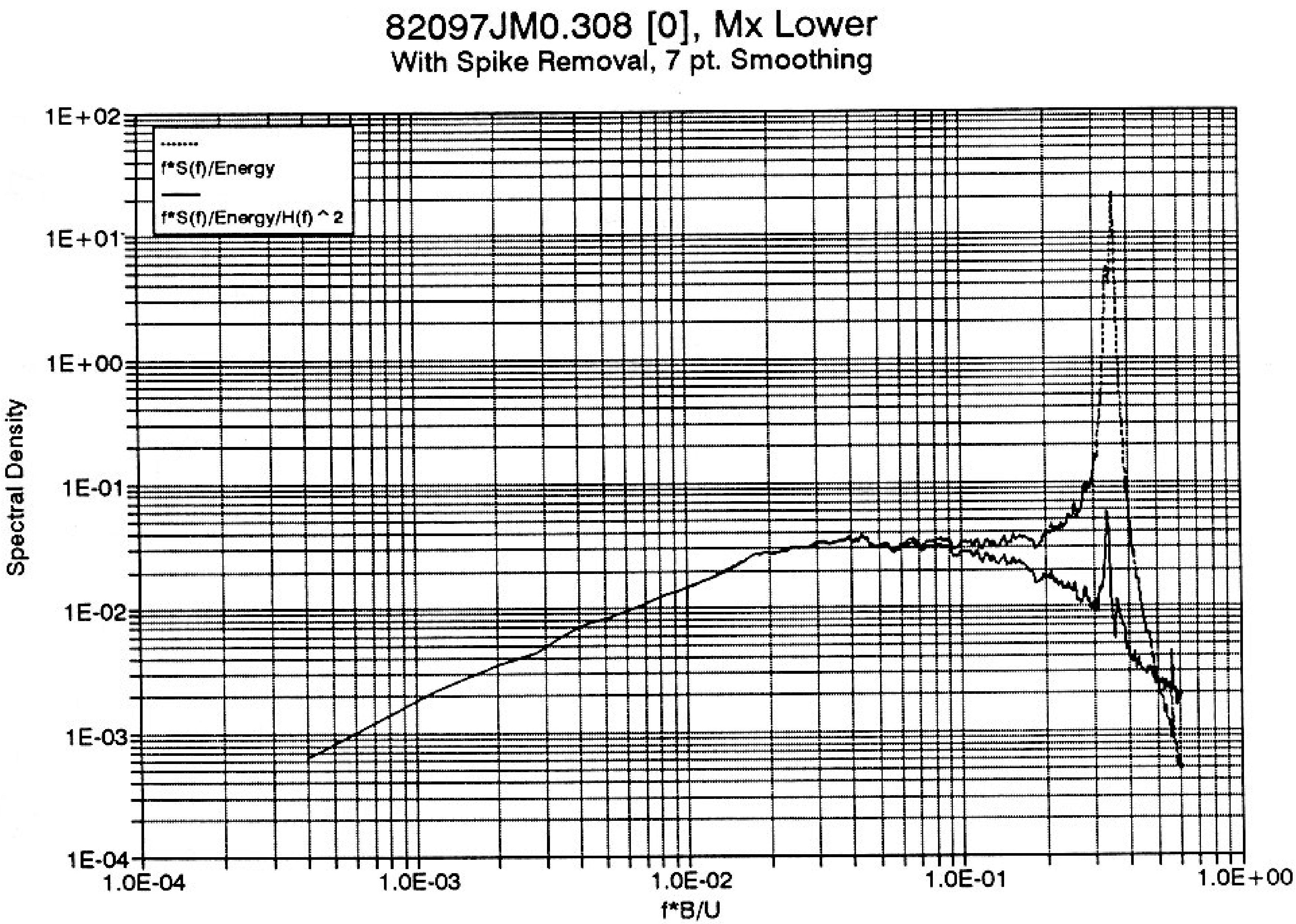
High-frequency force balance tests on the Leaning Tower of Pisa



High-frequency force balance tests on the Leaning Tower of Pisa



High-frequency force balance tests on the Leaning Tower of Pisa



High-frequency force balance tests on the Leaning Tower of Pisa

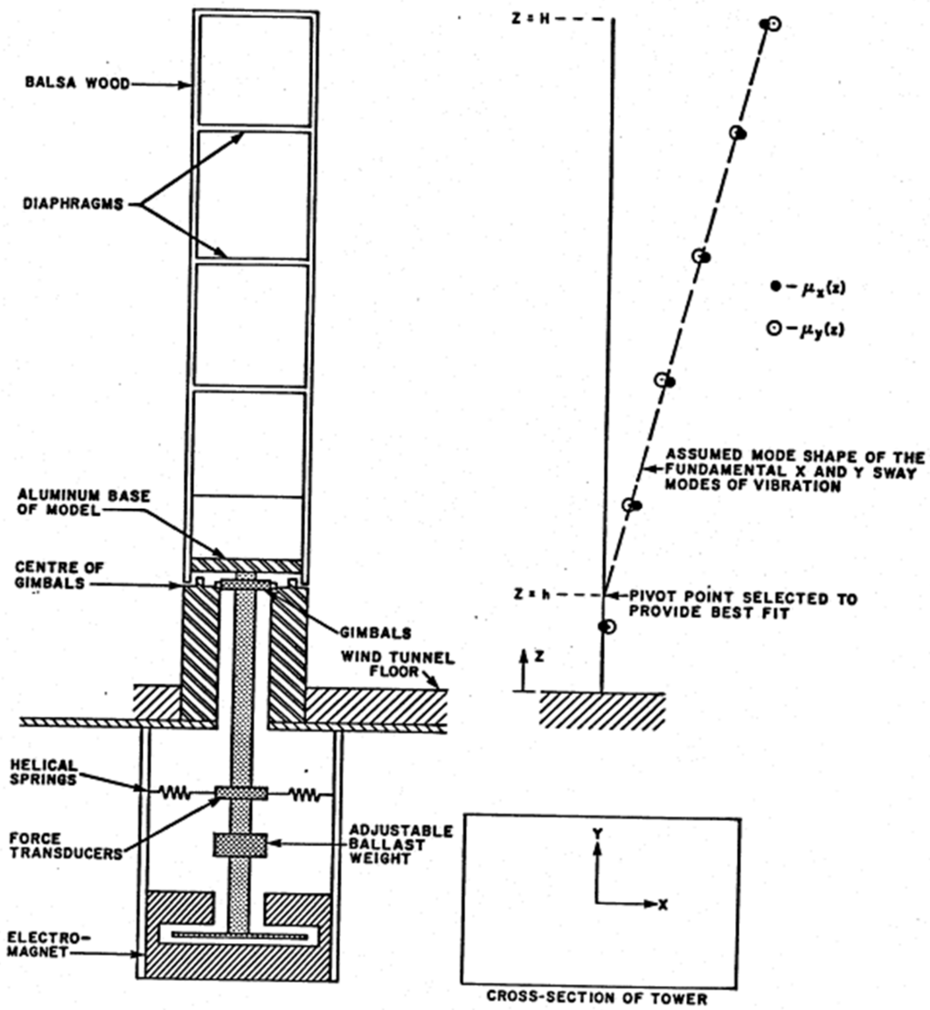
Correction procedures for nonlinear mode shapes

Kwok (1982)
Kareem (1984)
Vickery et al (1985)
Holmes (1987)
Boggs & Poterka (1989)
Xu & Kwok (1993)

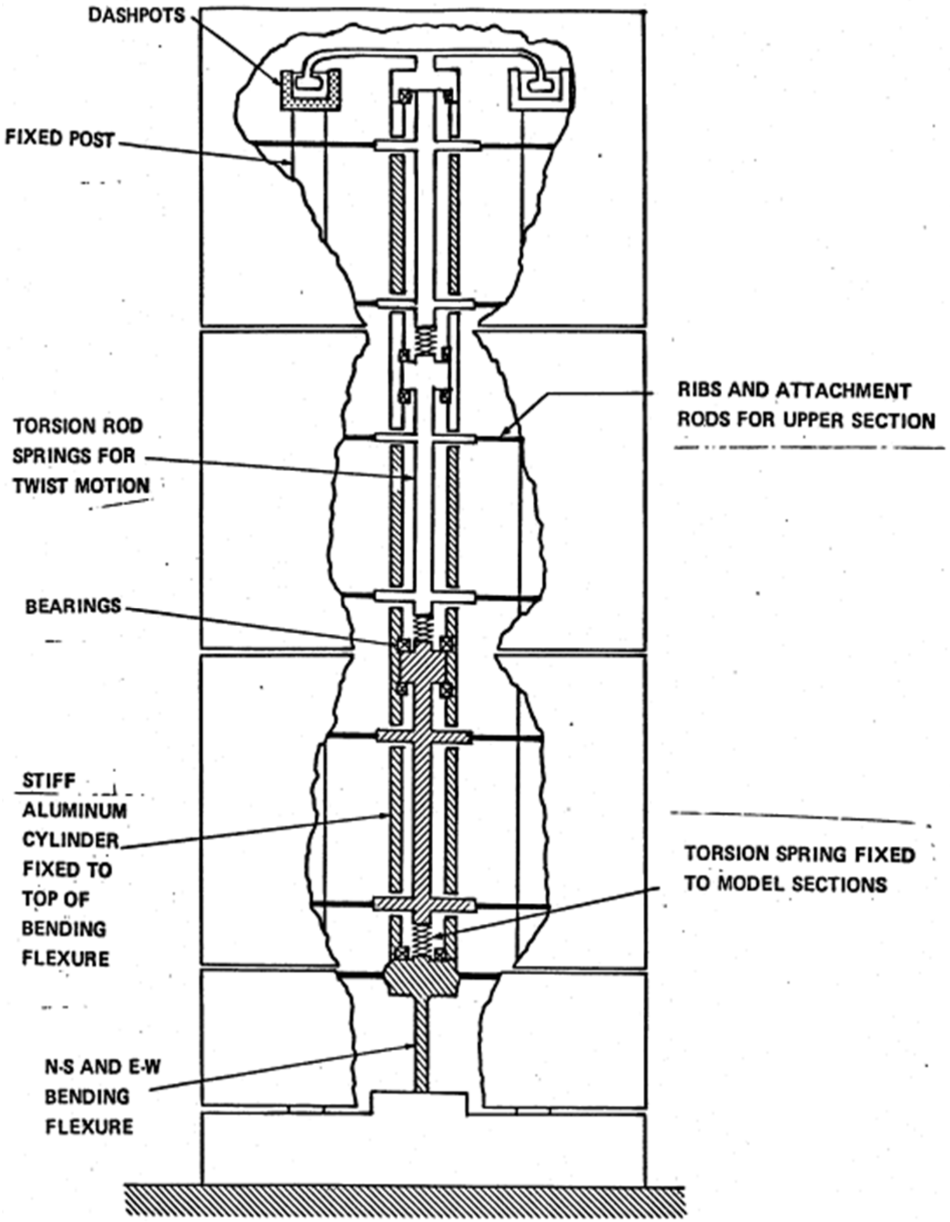
Procedures for determining the modal torque

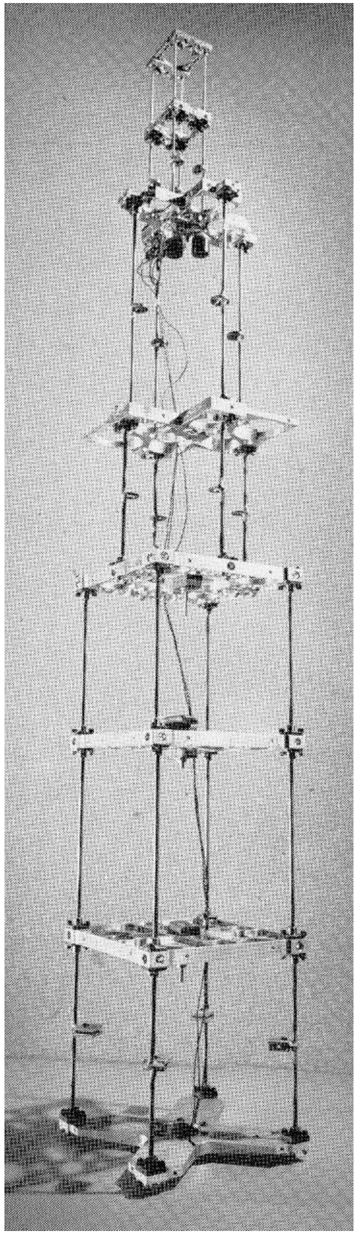
Tschanz & Davenport (1983)
Tallin & Ellingwood (1985)
Marukawa et al (1985)
Xu & Kwok (1993)

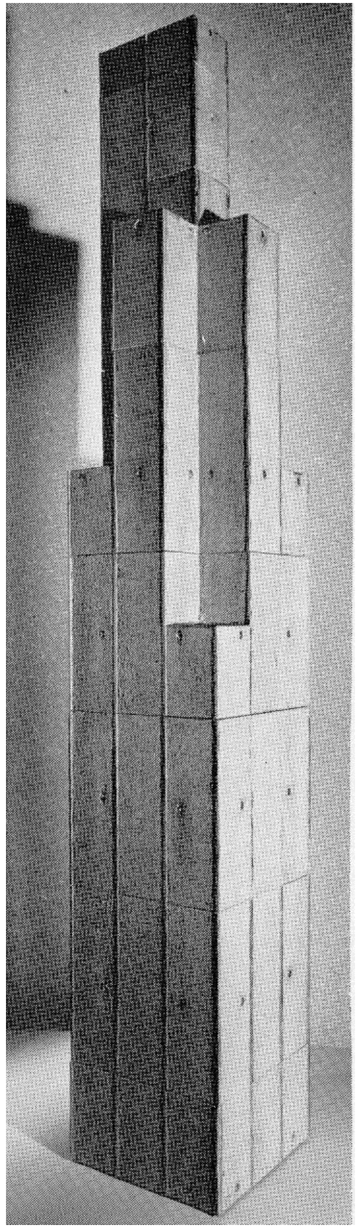
Correction techniques for non linear mode shapes



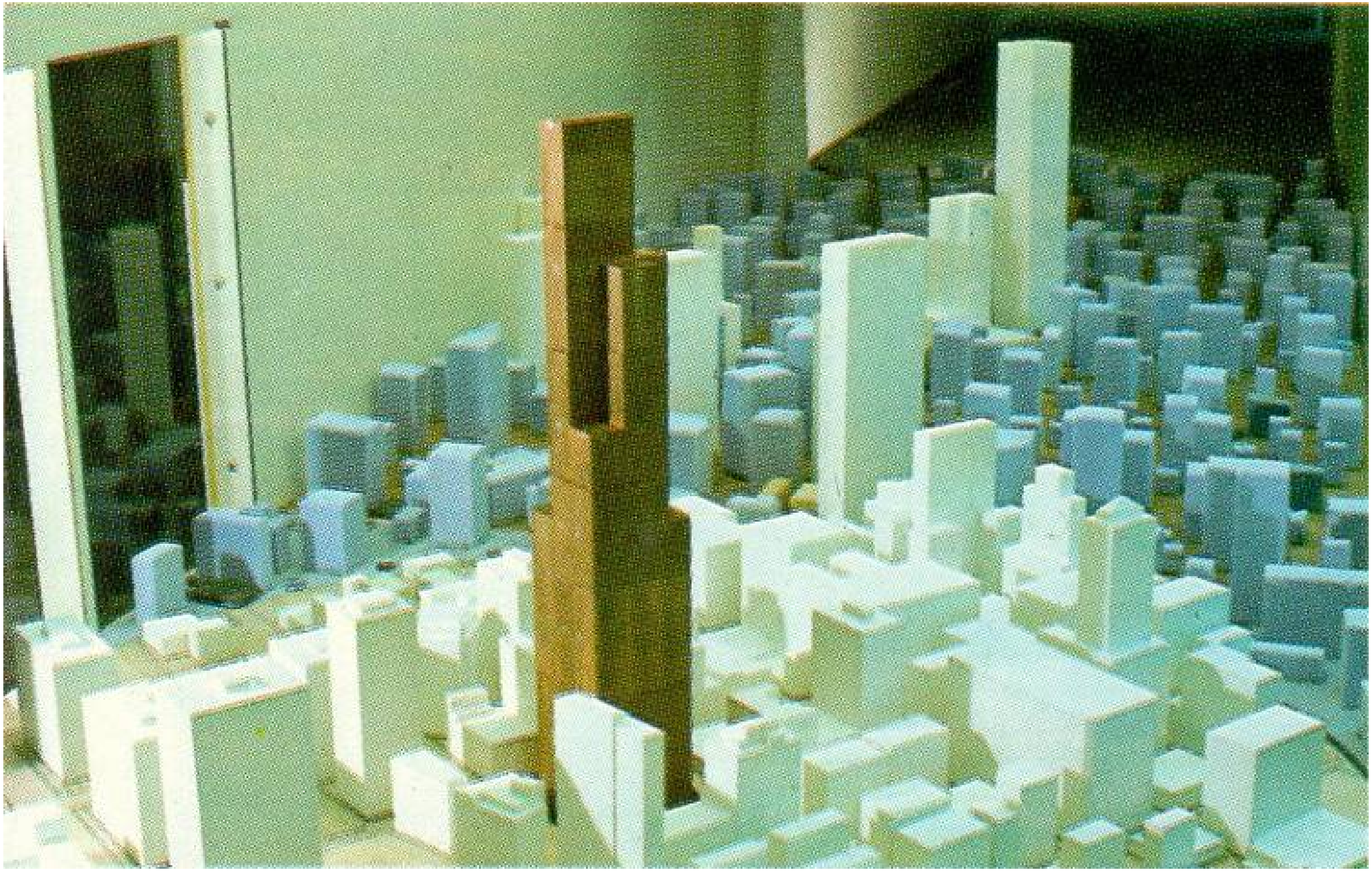
Flexible balance aeroelastic measurements



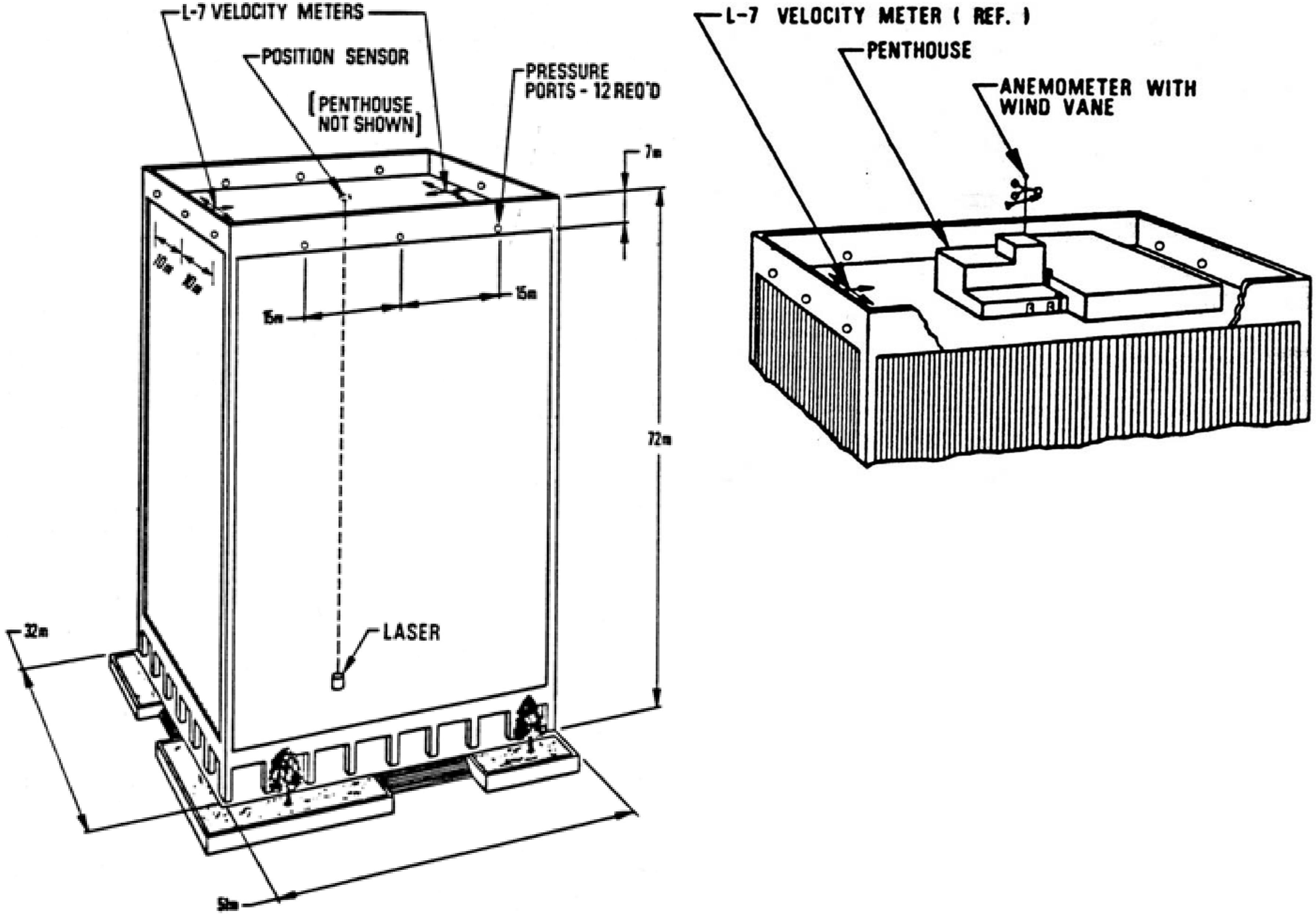




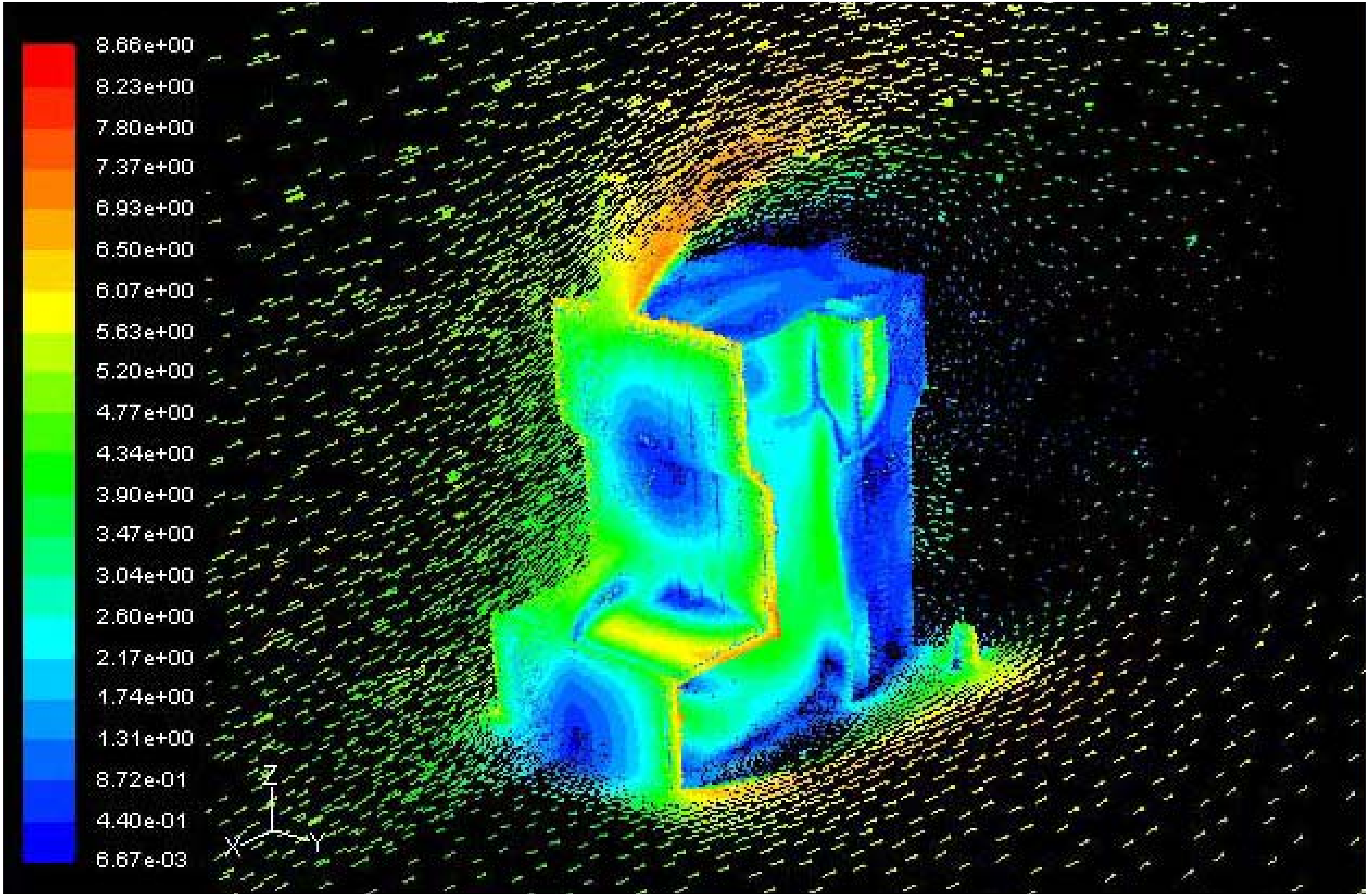
Fully aeroelastic measurements



Fully aeroelastic measurements

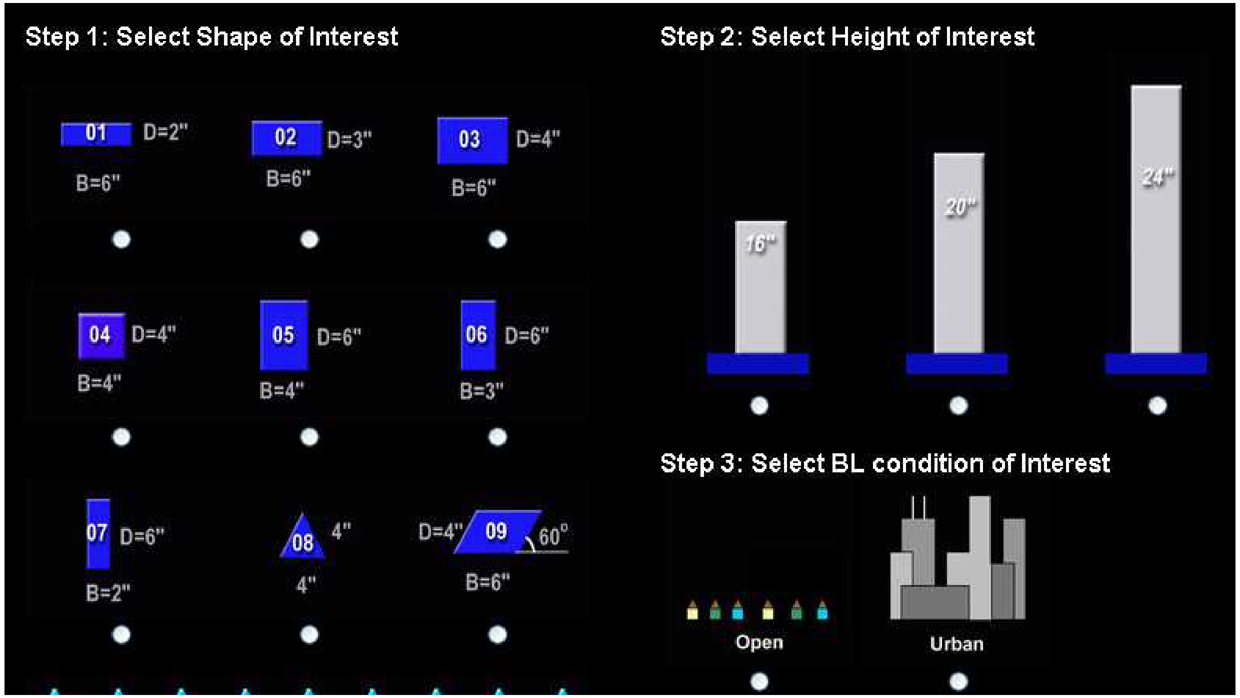


Full-scale tests



Computational Fluid Dynamics (CFD) models

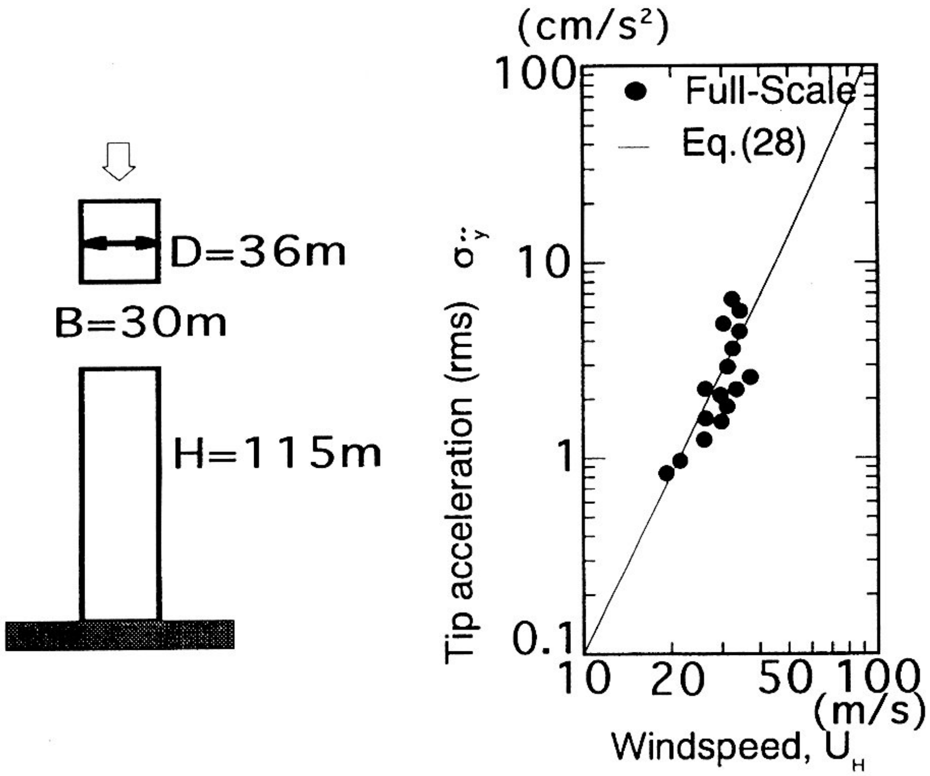
NatHaz Aerodynamic Data Base, Notre Dame, Indiana, U.S.

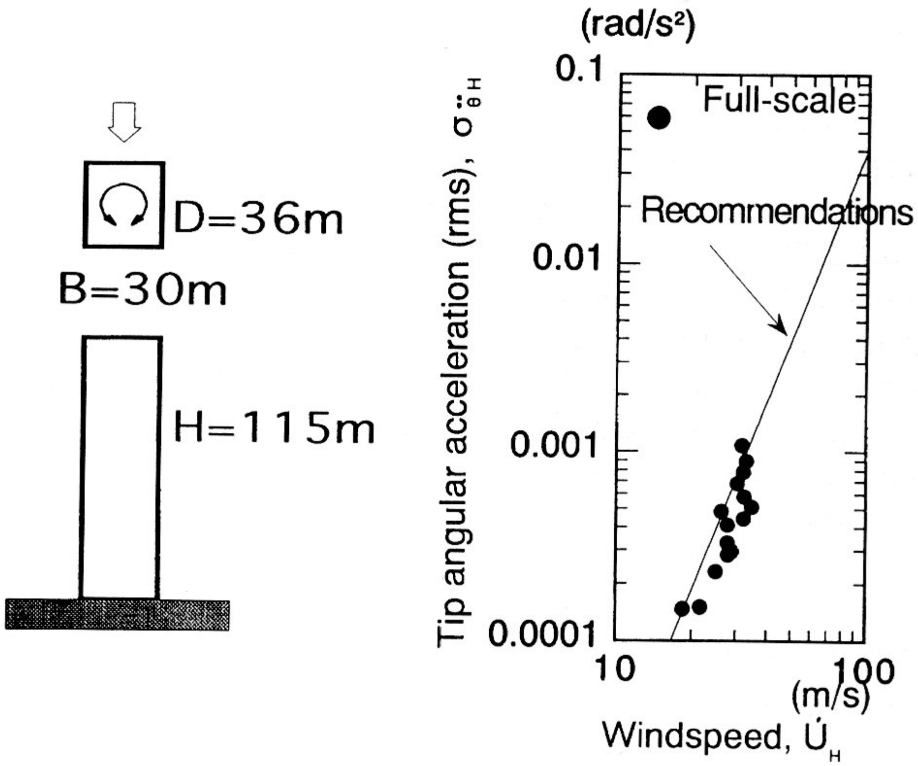


Model #	1	2	3	4	5	6	7	8	9
Shape									
D:B [in.]	2:6	3:6	4:6	4:4	6:4	6:3	6:2	4:4	4:6 (60°)

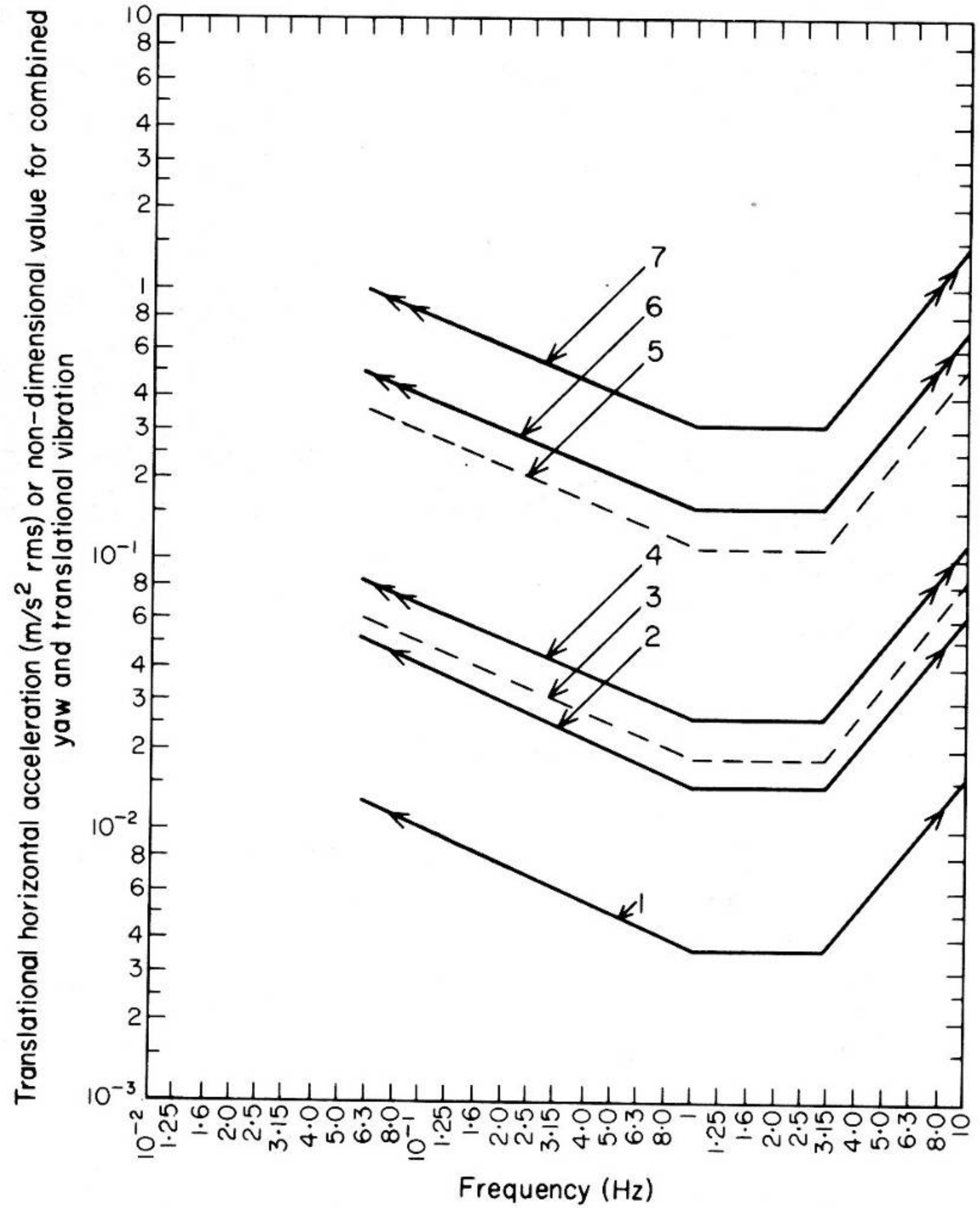
Electronic data bases

Architectural Institute of Japan (AIJ) Recommendations (1996)





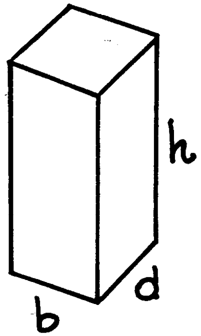
Analytical methods



1 Perceptible
2,3,4 Annoying
5,6,7 Intolerable

Human comfort criterion – Irwin (1981)

Esempio: Edificio multipiano metallico



$V_{ref} = 26\ m/s$; Categoria III

$b = d = 30\ m$

1) $h = 50\ m \Rightarrow n_1 = 0.92\ Hz$

$\delta = 0.05$

2) $h = 100\ m \Rightarrow n_1 = 0.46\ Hz$

$\delta = 0.05$

3) $h = 200\ m \Rightarrow n_1 = 0.23\ Hz$

$\delta = 0.05$

$\bar{R} = 5$ anni $\Rightarrow V_{ref} = 26 \times 0.85 = 22.1\ m/s$

Alongwind Response	Edificio 1	Edificio 2	Edificio 3
$W(h)$ (N/m^2)	1256	1609	2088
$X_{max}(h)$	h/6165	h/2371	h/902
$\sigma_{\ddot{x}}(h)$ (m/s^2)	0.010	0.021	0.039

Nota: W, X_{max} calcolati per $V_{ref} = 26\ m/s$

$\sigma_{\ddot{x}}$ calcolato per $V_{ref} = 22.1\ m/s$

ACROSS-WIND RESPONSE (Japanese code)

$H = 200\ m$, $B = D = 30\ m$

$V_{ref} = 26\ m/s$, category 3, $z_0 = 0.1\ m$, $K_r = 0.2$

$n_1 = 0.23\ Hz$, $\delta = 0.05$

$$W_L(Z) = 3 q_H C'_L g_L \sqrt{1 + R_L} \left(\frac{Z}{H}\right)$$

$q_H = \frac{1}{2} \rho U_H^2$; $U_H = V_{ref} K_r \ln(H/z_0) = 26 \times 0.2 \times \ln(200/0.1) = 39.52\ m/s$

$q_H = 976.38\ N/m^2$

$C'_L = 0.0082 (D/B)^3 - 0.071 (D/B)^2 + 0.22 (D/B) = 0.1572$

$g_L = \sqrt{2 \ln(600 n_0) + 1.2} = 3.325$

$R_L = \frac{\pi F_L}{4 \eta_f}$; $\eta_f = \delta / 2\pi = 0.008$

$$F_L = \sum_{1}^{m} {}_j \frac{4 \kappa_j (1 + 0.6 \beta_j) \beta_j}{\pi} \frac{(n_0 / n_{sj})^2}{\left[1 - (n_0/n_{sj})^2\right]^2 + 4 \beta_j^2 (n_0/n_{sj})^2}$$

$m = 1$, $\kappa_1 = 0.85$, $\beta_1 = 0.169$, $n_{s1} = 0.119\ Hz \Rightarrow F_L = 0.095 \Rightarrow$

$R_L = 9.34 \Rightarrow W_L(Z) = 3 \times 976.38 \times 0.1572 \times 3.325 \times \sqrt{1 + 9.34}\,(Z/H) \Rightarrow$

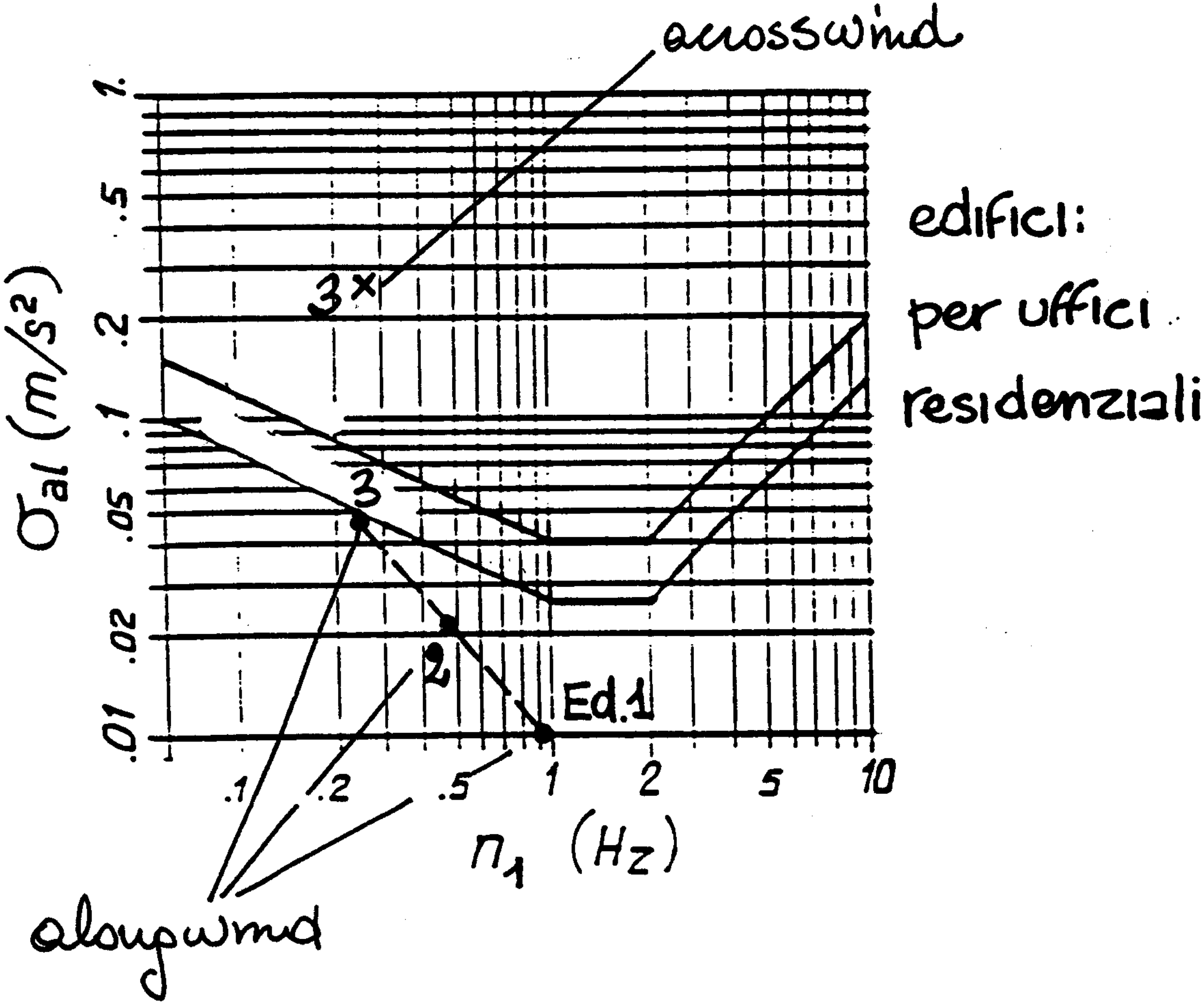
$W_L(Z) = 4923.17\,(Z/H)\ N/m^2$ (alongwind $W(h) = 2088\ N/m^2$)

Acceleration (commentary)

$$\sigma_{\ddot{y}}(z) = 3 q_H C'_L \frac{B}{m} \sqrt{R_L} \left(\frac{Z}{H}\right) \qquad m = 180\,000\ kg/m$$

$$\sigma_{\ddot{y}}(H) = 3 \times 976.38 \times 0.1572 \frac{30}{180\,000} \sqrt{9.34} = 0.235\ m/s^2$$

(alongwind $\sigma_{\ddot{x}}(h) = 0.039\ m/s^2$)



Acceleration control for habitability