Lecture 6

Wind Resistant Design
AIJ Recommendations for Wind Loads on Buildings

Tokyo Polytechnic University
The 21st Century Center of Excellence Program

Yukio Tamura

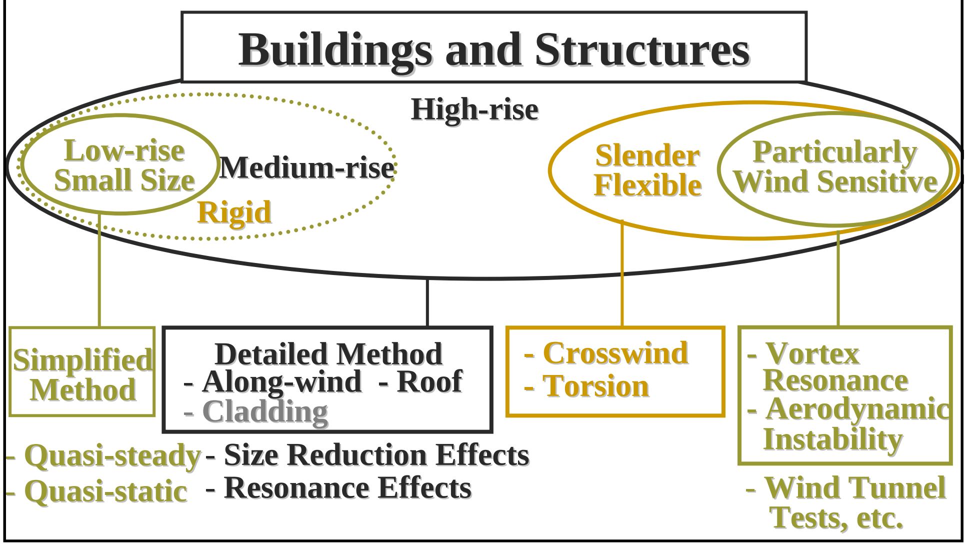
Background

- Building Standard Law of Japan (BSLJ) --- Minimum building design requirements
  - completely revised in 2000
  - Performance Based Design (PBD)
- AIJ Recommendations for Loads on Buildings (AIJ-RLB) 1993
  - to be revised in 2004

Major Revisions

- Introduction of the wind directionality factor (8 wind directions);
- Explicit introduction of wind load combinations;
- Correction and addition of topographic effects;
- Substantial fulfillment of aerodynamic shape factors

Wind Load Estimation in AIJ-RLB



Design Wind Speed U_H (m/s)

$$U_H = U_0 K_D E_H k_{rW}$$

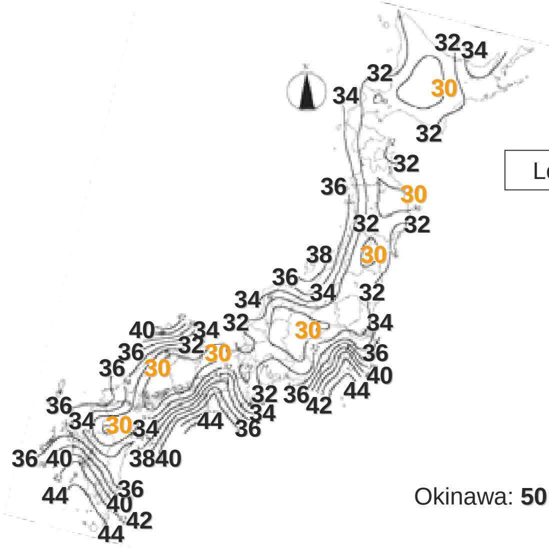
U_0 : Basic wind speed
K_D : Wind directionality factor
E_H : Wind speed profile factor
k_{rW} : Return period conversion factor

Basic Wind Speed

- Meteorological Standard Condition
  - 10min mean
  - 10m above ground
  - Open flat terrain
  - 100-year-recurrence
- Typhoon Winds : Monte-Carlo Simulation
- Synoptic Winds : Meteorological Data

Combined probability

Basic Wind Speed U_0 (m/s)

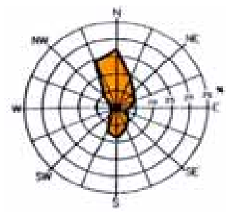


Lower Limit: 30m/s

Okinawa: **50m/s**

Orientation of Building and Wind Direction

- *B* = 20m, *D* = 40m, *H* = 40m



Maximum Acceleration	⇩	63%	⇩	100%
Maximum Displacement		50%		100%

Wind Directionality Factor

- Davenport (1969)
- Holmes (1981)
- Cook (1983)
- Melbourne (1984, 1990)
  → AS 1170.2 (1989)
  AS/NZS 1170.2 (2002)
- Simiu & Heckert (1998)

Wind Directionality Factor in Major Codes

- ASCE 7-98
  - Buildings: 0.85 for all directions
    Chimneys: 0.9 or 0.95 for all directions
    Except for hurricane-prone regions
- AS/NZS1170.2(2002)
  - Tropical-cyclone-prone regions:
    0.95 or 1.0 for all directions
  - Non-tropical-cyclone-prone regions:
    Wind Direction Multiplier for 8 sectors

Wind Directionality Factor

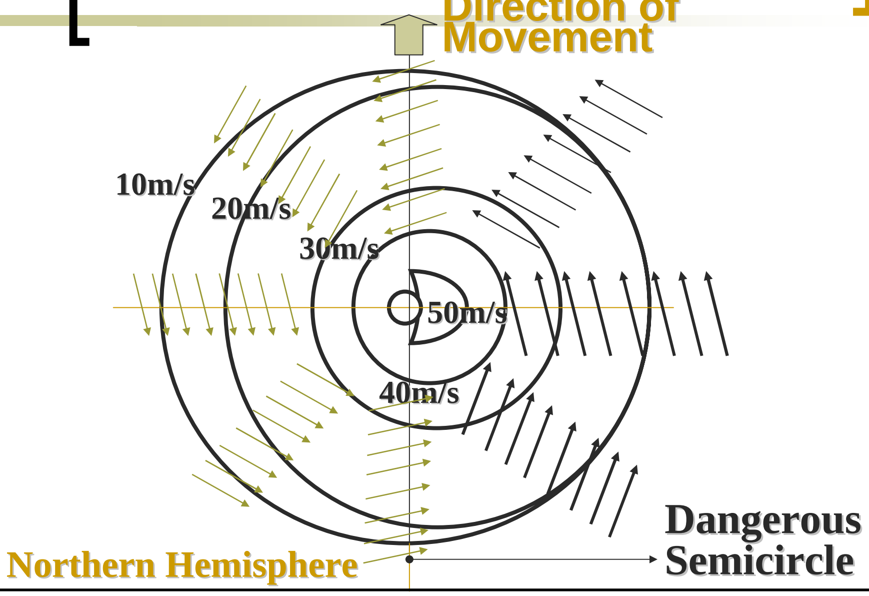
- Difficulty in tropical-cyclone-prone regions

  Meteorological records in Japan:

  - 75 years of reliable records at most
  - Approx. 3 landfalls/year of typhoons
  - Very few typhoon data in each sector divided into 8 or 16 sectors of azimuth for a given site

  → Large sampling error

Wind Distribution in Typhoon



Wind Directionality Factor in Japan

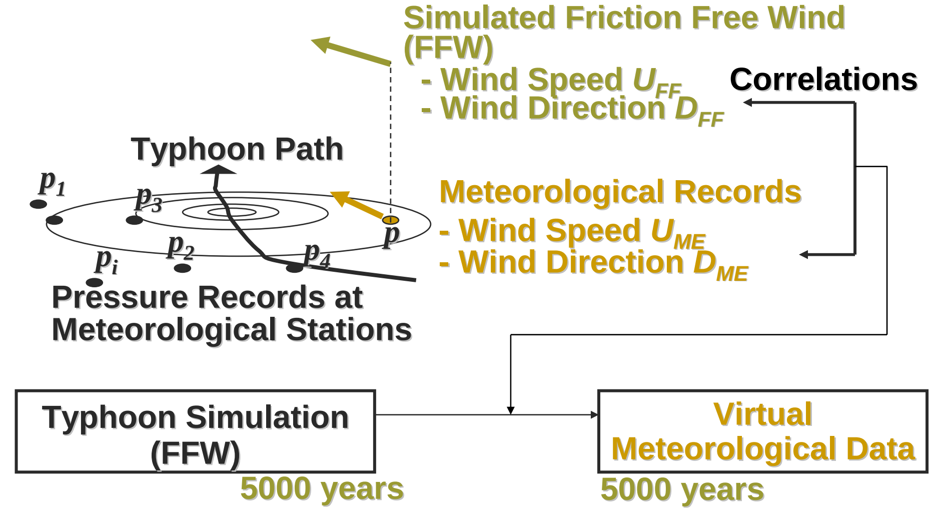
- Hybrid use of meteorological data during typhoon passage and Typhoon Simulation technique

  → Reflecting effects of large-scale topography and terrain roughness

  - Correlations between observed wind speed and simulated friction free wind speed

  - Correlations between observed wind direction and simulated friction free wind direction

Generation of Virtual Meteorological Data in Tropical Cyclone Prone Region



Generation of Virtual Meteorological Data in Tropical Cyclone Prone Region

Calculation of Correlations

Correlations Between Evaluated FFW (U_{FF}, D_{FF}) and Observed Wind Records (U_{ME}, D_{ME}) Using All Available Typhoon Records

Typhoon Simulations (5,000 years)

Monte-Carlo Simulation at Meteorological Stations

- **Wind Speed U_{SFF}**
- **Wind Direction D_{SFF} (FFW)**

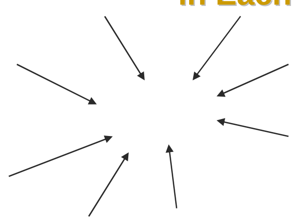
Virtual Meteorological Wind Data (5,000 years)

Probabilistic Conversion of Simulated FFW (U_{SFF}, D_{SFF}) to Virtual Meteorological Wind Data (U_{vir}, D_{vir})

Evaluation of Directional *R*-year Recurrence Wind Speed in Tropical Cyclone Prone Region

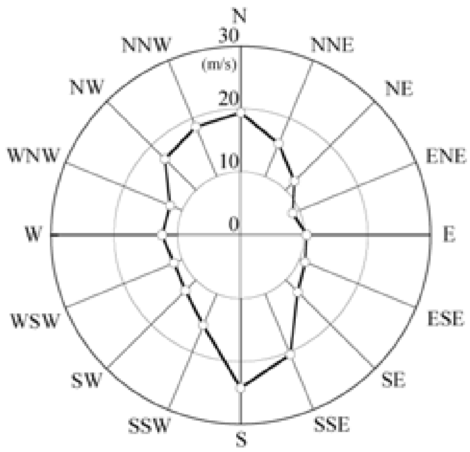
Virtual Long-term Meteorological Data

Sufficient Wind Records in Each Sector



***R*-year Recurrence Wind Speed for Each Wind Direction**

Wind Directionality
(Tokyo, 100-year Recurrence)



Hybrid Use of Typhoon Simulation and Meteorological Records

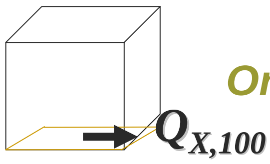
Equivalent Annual Exceedence Probability of Directional Wind Speed

- Corresponding to an annual exceedence probability of load effects (base shear, base moment, etc.) corresponding to 100-year recurrence
- Under different conditions:
  - load effects - building shape
  - orientation - geographic location
  - design target (structural frames, components and cladding)

Equivalent Directional Design Wind Speed U_D

- Annual probability of exceedence of a wind load effect = 1/100 (100-year Recurrence)

1. Calculation of 100-year recurrence wind load effect (e.g. internal force, peak pressure) based on the actual wind climate at a given site

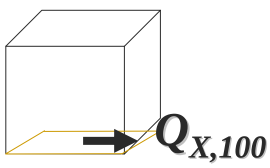


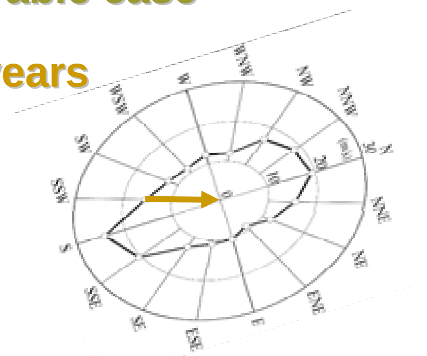
← Site, Building Shape, Orientation, Load Effect, etc.

Equivalent Directional Design Wind Speed U_D

2. Calculation of equivalent return period causing the same 100-year recurrence wind load effect in the most unfavorable case

≈ 150 – 200 years



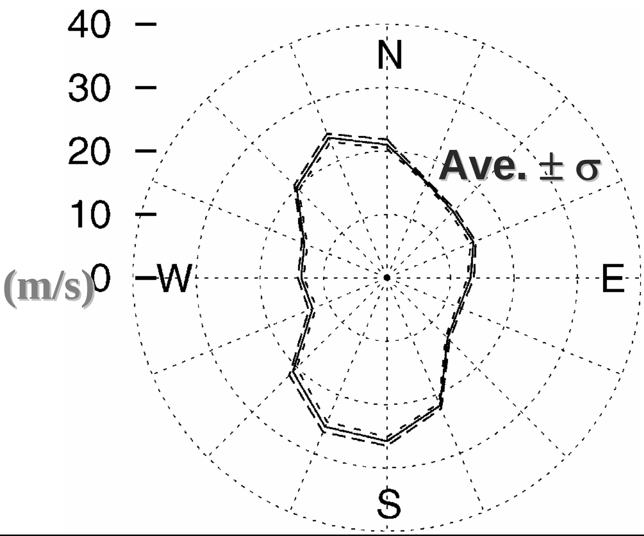


Equivalent Directional Design Wind Speed U_D

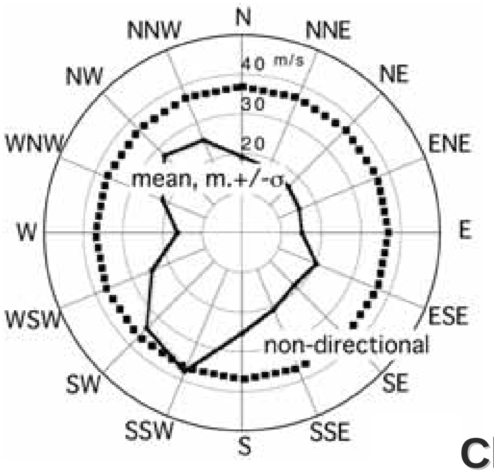
2. Calculation of equivalent return period causing the same 100-year recurrence wind load effect in the most unfavorable case

3. Calculation of average directional wind speeds U_D based on the equivalent return period for various cases at each meteorological site

Equivalent Directional Design Wind Speed U_D



Equivalent Directional Design Wind Speeds



Chiba

Wind Directionality Factor K_D (8 azimuths)

$$K_D = \frac{\text{Equivalent Directional Design Wind Speed}}{\text{Basic Wind Speed } U_0}$$

- If you have aerodynamic shape factors for all wind directions, K_D can be used directly.
- If you use aerodynamic shape factors C_f specified in the AIJ-RLB, there is a limitation.
  → Structural Frames : Specified method
  → Cladding/Components : $K_D = 1$

Wind Speed Profile Factor *E*

$$E = E_r E_g$$

E_r : Exposure factor for flat terrains

E_g : Topography factor for mean wind speed

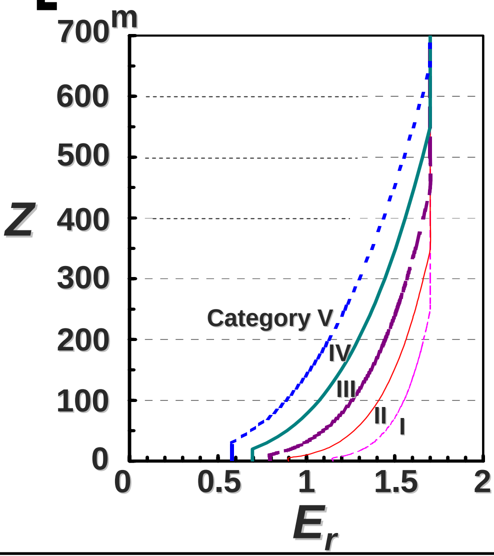
Exposure Factor for Flat Terrains E_r

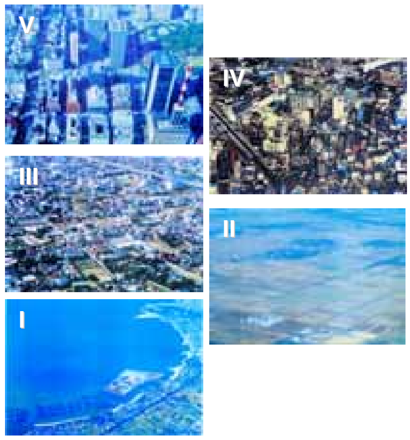
$$E_r = \begin{cases} 1.7\left(\dfrac{Z}{Z_G}\right)^{\alpha} & Z_b < Z \le Z_G \\ 1.7\left(\dfrac{Z_b}{Z_G}\right)^{\alpha} & Z \le Z_b \end{cases}$$

Z_G : Gradient height

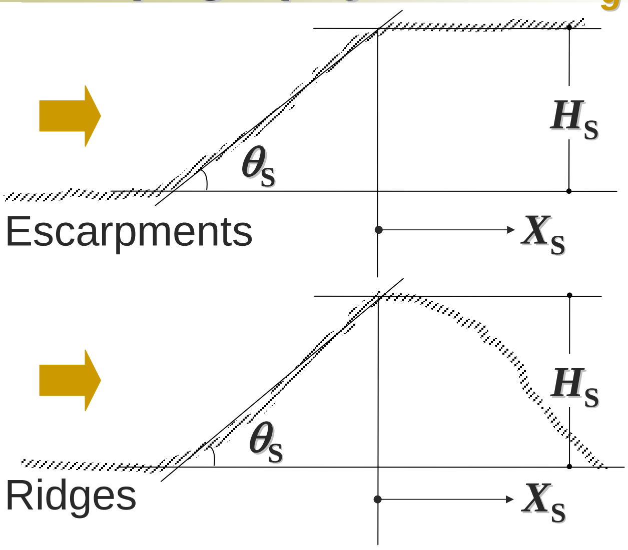
Z_b : Interfacial layer height

Exposure Factor for Flat Terrains E_r



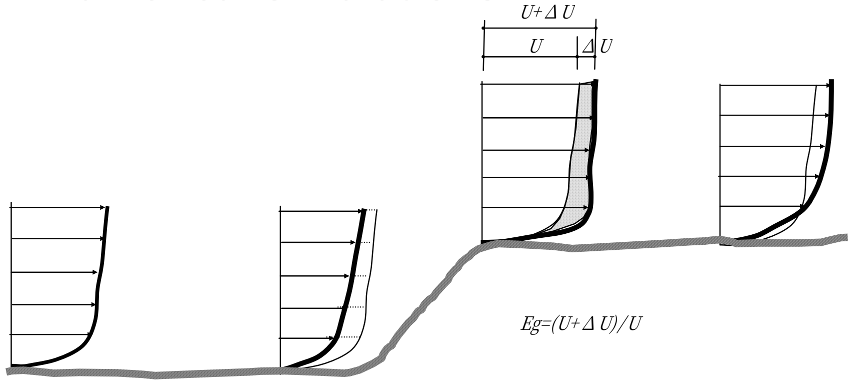


Topography Factor E_g



Topography Factor E_g

- A series of wind tunnel tests and numerical simulations



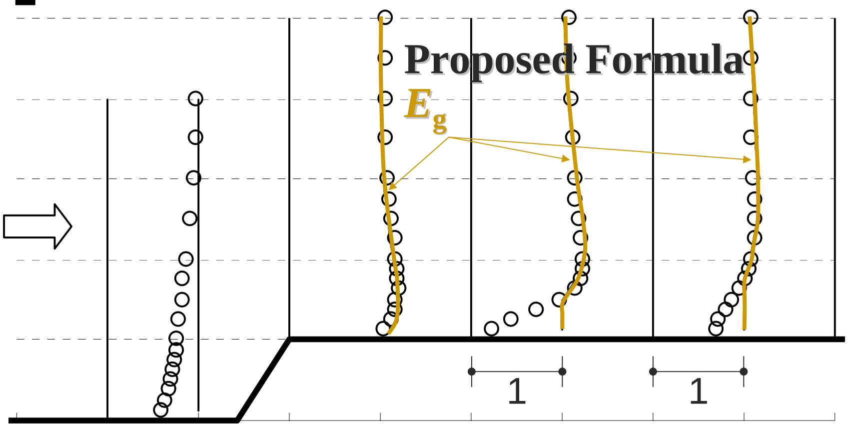
Topography Factor E_g

$$E_g = (C_1 - 1)\left\{ C_2 \left(\frac{Z}{H_S} - C_3 \right) + 1 \right\}$$

$$\times \exp\left\{ -C_2 \left(\frac{Z}{H_S} - C_3 \right) \right\} + 1 \quad \underline{\geq 1}$$

C_1, C_2 and C_3: Constants depending on slope angle and distance from upper edge

Topography Factor E_g



Return Period Conversion Factor k_{rW}

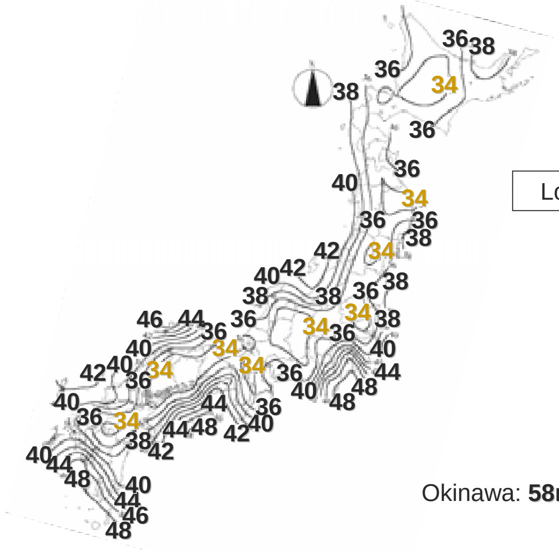
$$k_{rW} = 0.62(\lambda_U - 1)\ln r - 2.9\lambda_U + 3.9$$

$$\lambda_U = U_{500} / U_0$$

U_{500}: **500-year-recurrence wind speed for the meteorological standard conditions**

U_0 : **Basic wind speed (100-year-recurrence)**

500-year-recurrence Wind Speed U_{500} (m/s)



Lower Limit: 34m/s

Okinawa: **58m/s**

Turbulence Intensity I_Z at Height Z

$$I_Z = I_{rZ} E_{gI}$$

I_{rZ} : **Turbulence Intensity for flat terrains**

$$E_{gI} = \frac{E_I}{E_g}$$

- E_I: Topography factor for fluctuation wind speed σ_u
- E_{gI} : **Topography factor for turbulence intensity**
- E_g: Topography factor for mean wind speed U

Turbulence Intensity for Flat Terrains I_{rZ} at Height Z

$$I_{rZ} = \begin{cases} 0.1\left(\dfrac{Z}{Z_G}\right)^{-\alpha-0.05} & Z_b < Z \le Z_G \\ 0.1\left(\dfrac{Z_b}{Z_G}\right)^{-\alpha-0.05} & Z \le Z_b \end{cases}$$

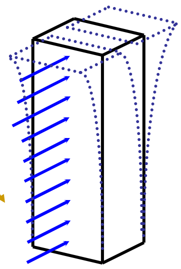
Turbulence Scale L_Z (m) at Height Z

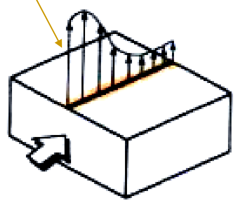
$$L_Z = \begin{cases} 100\left(\dfrac{Z}{30}\right)^{0.5} & 30\text{m} < Z \le Z_G \\ 100 & Z \le 30\text{m} \end{cases}$$

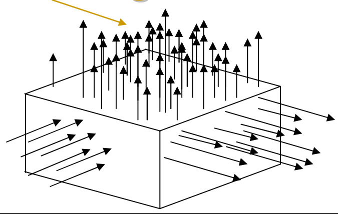
for every terrain category

Wind Loads Specified in AIJ-RLB

- For Main Frames
  - Horizontal Along-wind Load
    Ccrosswind Load
    Torsional Load
  - Roof Wind Load
- For Cladding / Components
  - Peak Cladding Load







Along-wind Loads on Ordinary Buildings W_D (N) at Height Z

$$W_D = q_H C_D G_D A$$

q_H : Velocity pressure at reference height H

C_D : Aerodynamic shape factor

G_D : Gust loading factor

A : Projected area

- GLF based on Base Bending Moment (Zhou & Kareem, 2001)

GLF for Along-wind Loads on Ordinary Buildings

$$G_D = 1 + g_D \frac{C_g'}{C_g}\sqrt{1+\phi_D{}^2 R_D}$$

g_D : Peak factor

C_g' and C_g : Fluctuating and mean coefficients for along-wind OTM

ϕ_D : Correction factor depending on mode shape

R_D : Resonance factor

Wind Loads on Roof Structures W_R (N)

$$W_R = q_H C_R G_R A_R$$

q_H : Velocity pressure at reference height H

$C_R = C_{pe} - C_{pi}$: Aerodynamic shape factor

G_R : Gust loading factor

A_R : Subjected area for roof beam

GLF for Wind Loads on Roof Structures

$$G_R = 1 \pm \frac{\sqrt{12.3 r_{\mathrm{Re}}^2 (1 + R_{Re}) + 0.3 r_c{}^2}}{|1 - r_c|} \qquad C_{pi} = -0.4, C_R \neq 0$$

$$C_R G_R = \pm 0.25 \sqrt{12.3 r_{\mathrm{Re}}^2 (1 + R_{Re}) + 0.3} \qquad C_{pi} = -0.4, C_R = 0$$

$$G_R = 1 \pm \sqrt{12.3 r_{\mathrm{Re}}^2 (1 + R_{Re}) + 0.3 r_c{}^2} \qquad C_{pi} = 0$$

$r_{\mathrm{Re}}, R_{\mathrm{Re}}$, and r_c : **Parameters depending on roof beam direction, dynamic characteristics of roof structure, and wind characteristics**

Along-wind Loads on Lattice Towers W_D (N) at Height Z

$$W_D = q_Z C_D G_D A_F$$

- q_Z : **Velocity pressure at height Z**
- C_D : **Aerodynamic shape factor**
- G_D : **Gust loading factor**
- A : **Projected area**

GLF for Along-wind Loads on Lattice Towers

$$G_D = 1 + g_D \frac{C'_g}{C_g} \phi_D \sqrt{1 + R_D}$$

g_D : Peak factor

C'_g and C_g : Fluctuating and mean coefficients for along-wind OTM

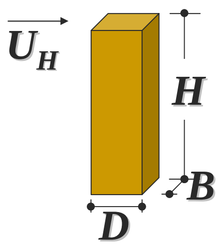
ϕ_D : Correction factor depending on mode shape

R_D : Resonance factor

Crosswind Loads and Torsional Loads

Slender and flexible buildings to satisfy following condition:

$$\frac{H}{\sqrt{BD}} \geq 3$$



Crosswind Loads on Buildings W_L (N) at Height Z

$$W_L = 3 q_H C'_L A \frac{Z}{H} g_L \sqrt{1 + \phi_L^2 R_L}$$

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

g_L : Peak factor

ϕ_L : Correction factor for mode shape

R_L : Resonance factor

Torsional Wind Loads on Buildings W_T (Nm) at Height Z

$$W_T = 1.8 q_H C'_T A B \frac{Z}{H} g_T \sqrt{1 + \phi_T^{\,2} R_T}$$

$$C'_T = \{0.0066 + 0.015 (D/B)^2\}^{0.78}$$

g_T : Peak factor

ϕ_T : Correction factor for mode shape

R_T : Resonance factor

Correction Factors Depending on Mode Shape ϕ

- **Ordinary buildings**

$$\mu = \left(\frac{Z}{H}\right)^{\beta}$$

Mode shape

$$\phi_D = \frac{1-0.4\ln\beta}{2+\beta}\frac{M}{M_D}$$ Along-wind loads

$$\phi_T = \frac{M\left(B^2+D^2\right)}{36 I_T}\left(\frac{Z}{H}\right)^{\beta-1}(1-0.4\ln\beta)$$ Crosswind loads

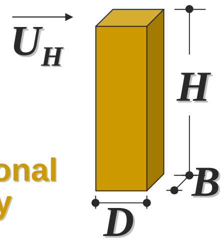
$$\phi_L = \frac{M}{3M_L}\left(\frac{Z}{H}\right)^{\beta-1}(1-0.4\ln\beta)$$ Torsional wind loads

- **Lattice Towers**

$$\phi_D = \frac{M}{5M_D}\left\{\left(0.5\frac{B_H}{B_0}-0.3\right)(\beta-2)+1.4\right\}(1-0.4\ln\beta)$$ Along-wind loads

Vortex Resonance and Aerodynamic Instabilities

- **Particularly wind-sensitive buildings to satisfy following conditions:**



$$\frac{H}{\sqrt{BD}} \geq 4$$

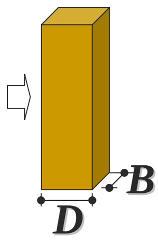
Non-dimensional onset velocity

$$\text{and}\ \left(\frac{U_H}{f_L\sqrt{BD}} \geq 0.83U^*_{Lcr}\ \text{or}\ \frac{U_H}{f_T\sqrt{BD}} \geq 0.83U^*_{Tcr}\right)$$

f_L, f_T : Fundamental natural frequencies of crosswind vibration and torsional vibration

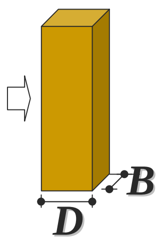
Non-dimensional Onset Velocity (Crosswind)

Terrain Category	Side Ratio D/B	Mass-Damping Parameter δ_L	Onset Velocity U^*_{Lcr}
I & II	$D/B \leq 0.8$	$\delta_L \leq 0.7$	$16\delta_L$
		$\delta_L > 0.7$	11
	$0.8 < D/B \leq 1.5$	All	$1.2\delta_L + 7.3$
	$1.5 < D/B \leq 2.5$	$\delta_L \leq 0.2$	2.3
		$0.2 < \delta_L \leq 0.8$	12
		$\delta_L > 0.8$	$15\ \delta_L$
	$D/B > 2.5$	$\delta_L \leq 0.4$	3.7
		$\delta_L > 0.4$	Not occur
III, IV & V	$D/B \leq 0.8$	All	$4.5\delta_L + 6.7$
	$0.8 < D/B \leq 1.2$		$0.7\delta_L + 8.8$
	$D/B > 1.2$		11



Non-dimensional Onset Velocity (Torsional)

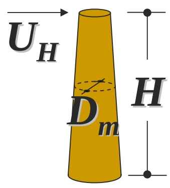
Side Ratio D/B	Mass-Damping Parameter δ_T	Onset Velocity U^*_{Tcr}
$D/B \leq 1.5$	$\delta_T \leq 0.05$	2
	$0.05 < \delta_T \leq 0.1$	11
	$\delta_T > 0.1$	Not occur
$1.5 < D/B \leq 2.5$	$\delta_T \leq 0.05$	2
	$0.05 < \delta_T \leq 0.15$	$4 + 8\delta_T$
	$\delta_T > 0.15$	$8.6 + 7.4\delta_T$
$2.5 < D/B \leq 5$	$\delta_T \leq 0.05$	2
	$\delta_T > 0.05$	$5 + 10.5\delta_T$



Vortex Resonance of Circular Cylinders

- Buildings with a circular plan to satisfy following conditions:

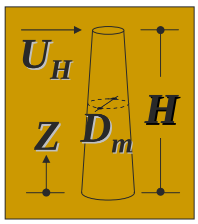
$$\frac{H}{D_m} \geq 7 \ \text{and} \ \frac{U_H}{f_L D_m} \geq 4.2$$



f_L : Fundamental natural frequency of crosswind vibration

Wind Loads on Circular Cylinders W_r (N) for Vortex Resonance at Height Z

$$W_r = 0.8 \rho U_r^2 C_r \frac{Z}{H} A$$

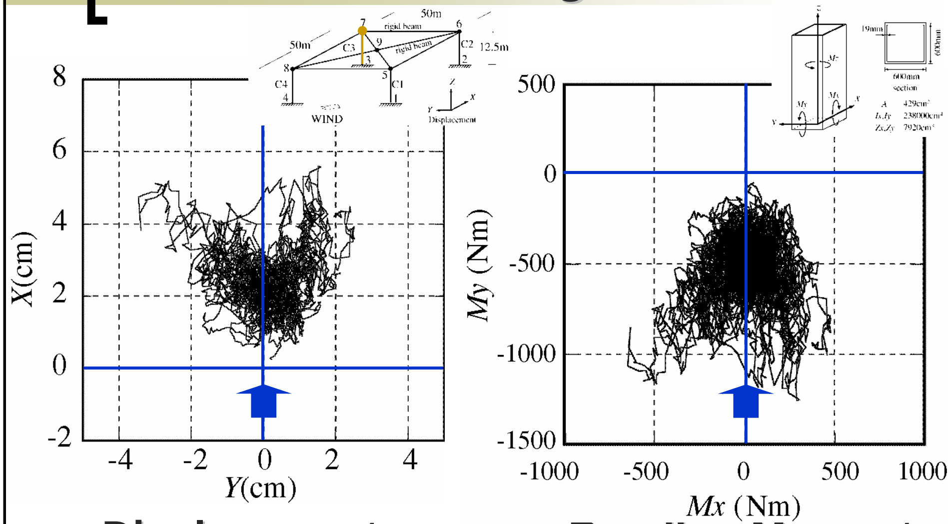


$U_r = 5 f_L D_m$: Resonance wind speed (m/s)

C_r : Equivalent aerodynamic shape factor for vortex resonance
- tabulated in AIJ-RLB

f_L : Fundamental natural frequency of crosswind vibration

Phase-plane Expressions of Column Tip Displacements and Base Bending Moments



Displacement **Bending Moment**

Peak Normal Stresses in Column C1

(Low-rise Sq. Model, α =1/4)

Load Conditions	Tensile Stress kN/cm² Peak Value (P.F.)	Compressive Stress kN/cm² Peak Value (P.F.)
ALL : F_D F_L F_T M_D M_L M_T	5.4 (4.56)	– 4.7 (– 4.50)
Along-wind F_D only	4.2 (4.42)	– 4.1 (– 4.42)
Crosswind F_L only	1.7 (3.95)	– 1.8 (– 3.95)
Torsional Moment M_T only	0.9 (4.36)	– 0.9 (– 4.36)
ALL / Along-wind F_D only	130%	115%

- Ensemble averaged values of 12 samples
- The worst case was a 75% increase in tensile stress.

Combinations of Wind Load Components

- Low- and medium-rise buildings

  - Y. Tamura, H. Kikuchi and K. Hibi (2002)
  - H. Kikuchi, Y. Tamura and K. Hibi (2002)

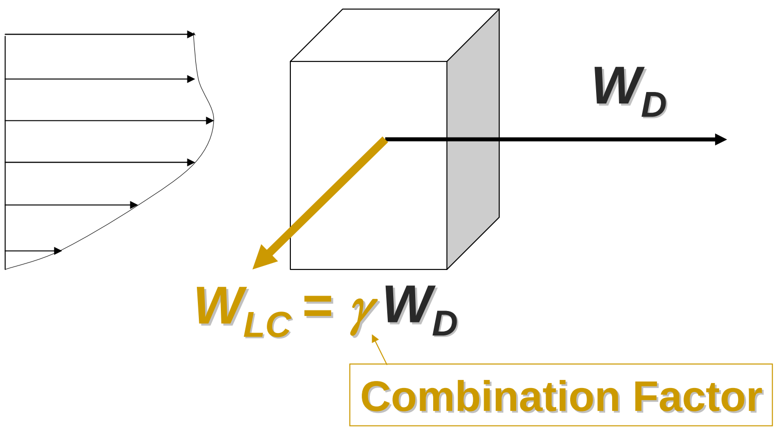
  Peak normal stresses in columns

- High-rise buildings

  - Asami (2000, 2002)

  Combination methods considering correlations of along-wind, crosswind and torsional responses

Wind Load Combination for Low- and Medium-rise Buildings



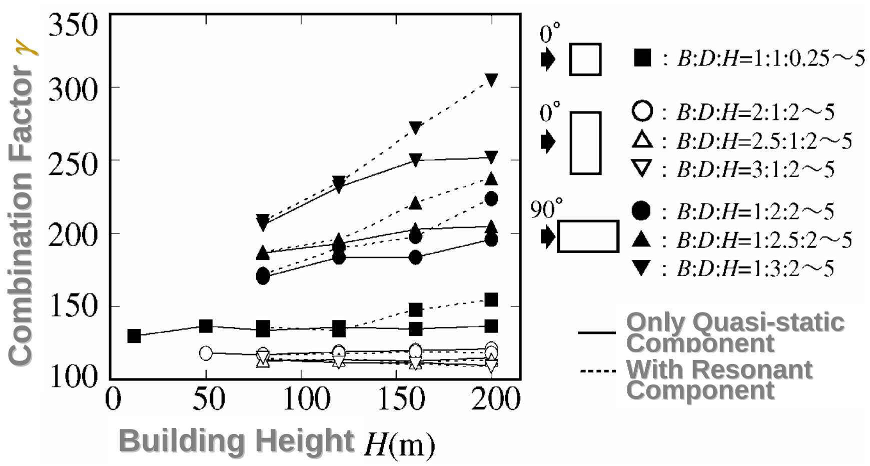
Combination Factor γ for Low- and Medium-rise Buildings

Combination Factor γ

$$= \frac{\text{Column Normal Stress by All Wind Force Components}}{\text{Column Normal Stress by Along-wind Force only}} - 1$$

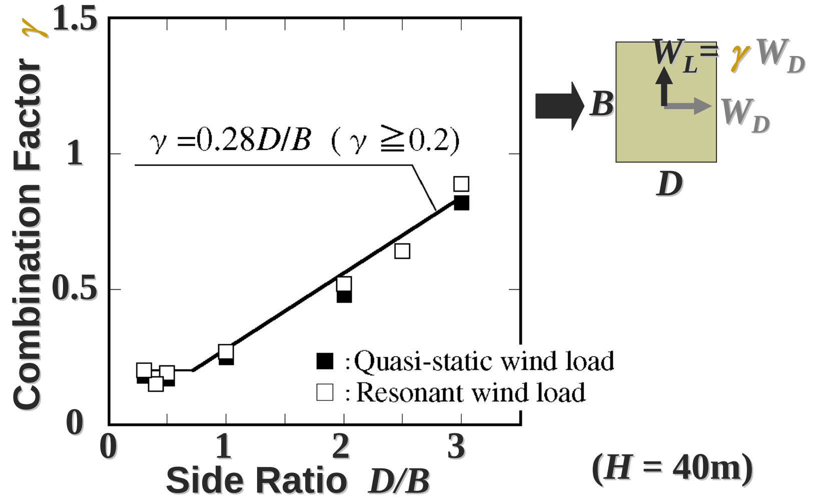
Combination Factor γ for Low- and Medium-rise Buildings

(Kikuchi, Tamura & Hibi, 2002)



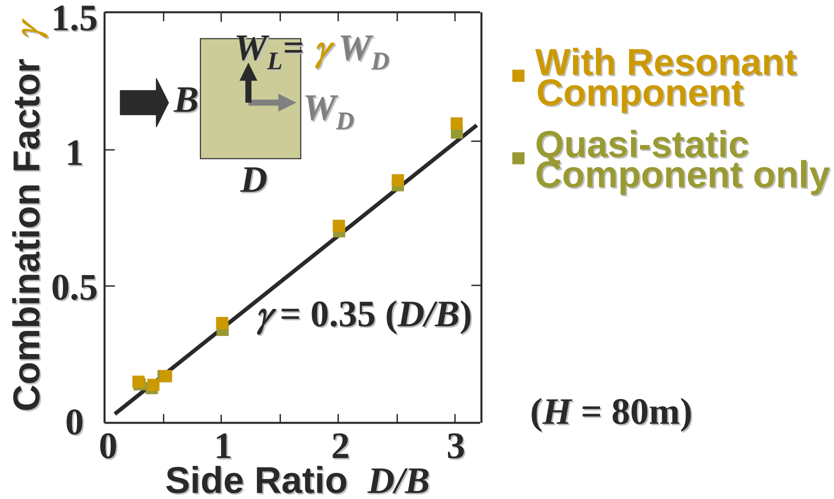
Combination Factor γ for Low- and Medium-rise Buildings

(Kikuchi, Tamura & Hibi, 2002)

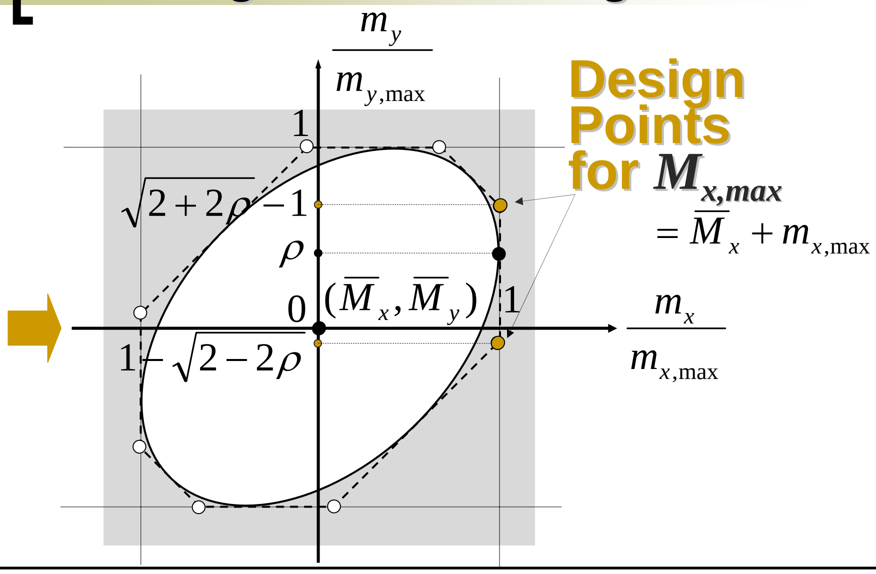


Combination Factor γ for Low- and Medium-rise Buildings

(Kikuchi, Tamura & Hibi, 2002)



Wind Load Combinations for High-rise Buildings



Wind Load Combinations for High-rise Buildings

Combination	Along-wind Load	Crosswind Load	Torsional Load
1	W_D	$0.4\,W_L$	$0.4\,W_T$
2	$\left(0.4+\frac{0.6}{G_D}\right)W_D$	W_L	$\left(\sqrt{2+2\rho_{LT}}-1\right)W_T$
3	$\left(0.4+\frac{0.6}{G_D}\right)W_D$	$\left(\sqrt{2+2\rho_{LT}}-1\right)W_L$	W_T

Correlation Coefficient ρ_{LT} between Crosswind Response and Torsional Response

- tabulated in AIJ-RLB
- depends upon D/B

f_θ / f_L

$f_1 B/U_H$

The smaller of f_θ and f_L

Combinations of Horizontal Wind Load and Roof wind Load

- It is recommended to simply superimpose the horizontal wind load and roof wind load.

- Y. Tamura, H. Kikuchi and K. Hibi (2003)

The vertical component of the wind force acting on medium-rise buildings tended to become largest when one of the horizontal wind force components reached its maximum value .

Wind Loads for Components and Cladding W_R (N)

$$W_C = q_H \hat{C}_C A_C$$

$$\hat{C}_C = \hat{C}_{pe} - C^*_{pi}$$

$\hat{C}_{pe}$: Peak external pressure coefficient

C^*_{pi} : Coefficient accounting for the effect of the internal pressure fluctuation → Equivalent internal pressure coefficient

A : Tributary area

Aerodynamic Shape Factors

- External wind pressure coefficients C_{pe} for structural frames:
  - Buildings with rectangular sections (H>45m)
  - Buildings with rectangular sections with flat, shed, or gable roofs ($H \leq$45m)
  - Circular arc roofs ($H \leq$45m)
  - Dome roofs
- Internal wind pressure coefficients C_{pi} for structural frames
  - Buildings without dominant openings

Aerodynamic Shape Factors

- External wind force coefficients for structural frames: C_D, C_X, C_Y
  - Buildings with circular sections
  - Pitched free roofs with a rectangular plan
  - Lattice structures
  - Fences
  - Members with various sections
  - Nettings

Aerodynamic Shape Factors

- External peak pressure coefficients $\hat{C}_{pe}$ for cladding and components:
  - Buildings with rectangular sections (*H*>45m)
  - Buildings with rectangular sections with flat, shed, or gable roofs (*H*≤45m)
  - Buildings with circular sections
  - Circular arc roofs (*H*≤45m)
  - Dome roofs
- Coefficients accounting for the effect of the internal pressure fluctuation for cladding and components C^*_{pi}
  - Buildings without dominant openings

Aerodynamic Shape Factors

- External peak wind force coefficients for cladding and components: $\hat{C}_C$

- Pitched free roofs with a rectangular plan

1-year-recurrence Wind Speed U_1 (m/s)

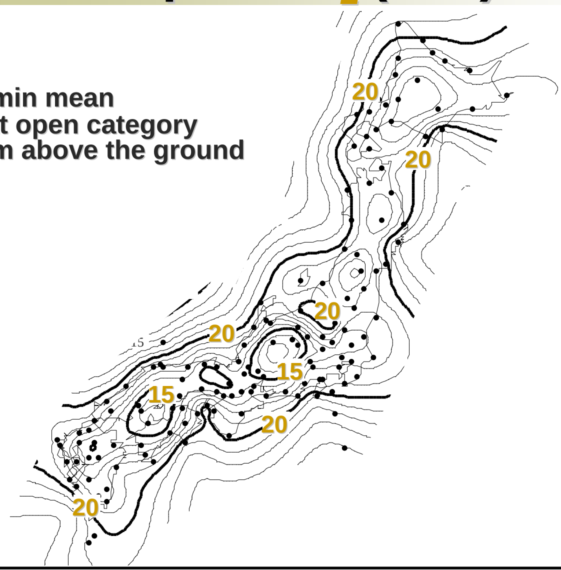
- AIJ Guidelines for the Evaluation of Habitability to Building Vibration (1991)

(Its revised version will be published in 2004)

- 1-year-recurrence peak acceleration has been applied for the evaluation

1-year-recurrence Wind Speed U_1 (m/s)

- 10min mean
- Flat open category
- 10m above the ground



Miscellaneous

- Evaluation formulae for along-wind, crosswind and torsional acceleration responses
- Interference effects of neighboring buildings
- Uncertainty and dispersion of parameters included in AIJ-RLB-2004

  - to achieve reliability based design