Estimation of Across-Wind Response of Tall Buildings

Evaluation du comportement au vent de bâtiments élevés

Bewertung von Gegenwindreaktionen hoher Gebäude

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SUMMARY

Across-wind responses of tall buildings were investigated on the viewpoint of carrying out an estimation using simple formula in Canadian Code. The shape effects of the various cross sections on the wind responses were made clear in order to get fundamental information concerned with applicability of the formula. The across-wind responses from the formula were also compared with the data from the full-scale measurements in order to examine the accuracy of the estimation using this formula.

RESUME

L'évaluation du comportement au vent de bâtiments élevés est réalisée sur la base d'une formule simplifiée, tirée des normes canadiennes. L'effet de la forme des différentes sections sur le comportement au vent a été étudié, afin d'obtenir l'information nécessaire pour l'application de la formule. Le comportement au vent selon la formule a été comparé avec des données de mesures en vraie grandeur, afin de contrôler la précision du calcul selon cette formule.

ZUSAMMENFASSUNG

Das Verhalten von Hochhäusern gegenüber Windeinflüssen wurde anhand einer vereinfachten Formel geschätzt die aus kanadischen Baunormen hervorgeht. Die durch die Querschnittform verursachten Auswirkungen des Windes wurden nachvollzogen, um grundlegende Informationen betreffend der möglichen Anwendung der Formel zu sammeln. Die mittels Formel gerechnete Windauswirkung wurde mit effektiven, an Gebäuden vollzogenen Messungen verglichen, um die Genauigkeit der Formel zu ewrmitteln.

1. INTRODUCTION

Serviceability requirements for tall buildings have recently attracted considerable attention in structural engineering practices. Wind-induced response is the most important factor in discussing the serviceability of tall buildings.

Across-wind acceleration is usually dominant in the response caused by strong winds. Therefore, the across-wind acceleration level is used in the investigation of the serviceability. A simple formula of the across-wind acceleration, such as the formula in the National Building Code of Canada[1] and the Australian Standard[2] are generally used to ensure that the accelerations are within acceptable limits at an early stage of practical design.

In this study, the across-wind acceleration of tall buildings was investigated and discussed from the viewpoint of the estimation using the simple formula in the National Building Code of Canada. The data not only from wind tunnel experiments but also from full-scale measurement was used in this investigation.

The authors first compared between the values derived from the formula with the values based on the data from wind tunnel experiments through the use of typical tall building models that had various sectional shapes. Their aim was to discuss the shape effect of the various cross sections which affected the across-wind acceleration, and to get fundamental information concerned with the applicability of the formula. We also investigated the affect of large sections constructed at the lower part of tall buildings with regard to the use of the formula.

Secondly, we studied the actual dynamic behavior caused by strong winds using the data from full-scale measurements for a high-rise residence. Based on the records obtained from those measurements, we expressed the relation between the across-wind acceleration and the mean wind speed to get some consideration for actual response characteristics caused by winds. The accelerations from the formula were also compared with the data from the measurement to examine the accuracy of the estimation which was made through the use of formula in the National Building Code of Canada.

2. ESTIMATION OF ACROSS-WIND ACCELERATION

2.1 Wind Tunnel Experiments

Wind tunnel experiments were performed to determine the spectral characteristics of wind force components on 3D cylinders for estimating across-wind acceleration. A boundary layer wind tunnel with a working section of 3.0m x 2.5m was used for five force component measurements of the 3D cylinders

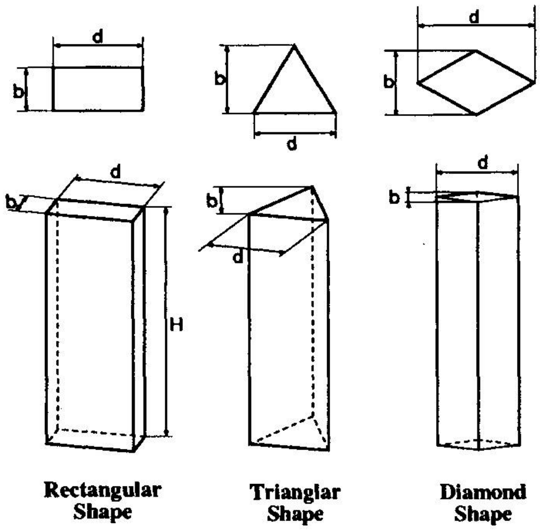

Fig.1 3D Cylinder Models

each of which had various cross sectional shapes with the same sectional area A of 0.01m², and the same height H of 0.4m as shown in Fig.1[3]. The shapes used were rectangular sections whose span ratio b/d (b:breadth, d:depth) was 0.33 - 3.0, triangular sections and diamond sections, each of which had the same aspect ratio H/B (B: a square root of A as a reference length of each section) of 4. Two boundary layer turbulent flows with the power law exponent of 0.20 and 0.35 for mean wind speed profile were produced for this study as shown in Table.1. A measurement of wind force was carried out through the use of a dynamic force balance which was installed at the bottom of the models. Coordinates are shown in Fig.2.

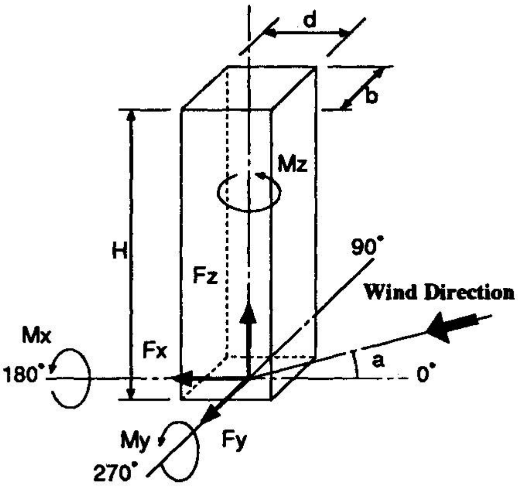

Fig.2 Coordinates

	Power Law Exponent α	Mean Wind Speed V_H (m/s)	Tubulence Intencity σ_v/V_H
Flow A	0.20	8.12	0.112
Flow B	0.35	6.92	0.156

Table.1 Characteristics of Flows

Figures 3,4,5 and 6 show the normalized power spectra of wind-induced generalized force $fS_{F1}(f)/(q_HBH)^2$ in an across-wind direction using the linear modal shape as the fundamental mode for each 3D cylinder, where q_H is the velocity pressure at the top of the cylinder, V_H is the mean wind speed at the top of the cylinder and V_H/fB is the reduced wind speed.

2.2 Across-Wind Acceleration

By using the normalized power spectra $fS_{F1}(f)/(q_HBH)^2$ obtained from the wind tunnel experiments, the r.m.s value of the response acceleration in an across-wind direction σ_a^S of a full scaled building can be calculated by following:

$$\sigma_a^S = \sqrt{\frac{\pi f_1 S_{F_1}(f_1)}{4\zeta_1 M_1^2}} \quad (\mathrm{cm/s^2}) \; , \qquad (1)$$

where f_1 is the fundamental natural frequency of the building, ζ_1 is the corresponding modal damping ratio and M_1 is the generalized modal mass of the building.

On the other hand, the r.m.s value of the across-wind acceleration σ_a^C from the formula in the National Building Code of Canada can be expressed as:

$$\sigma_a^C = \frac{2C_A}{3}\left(\frac{V_H}{f_1\sqrt{bd}}\right)^{3.3} f_1^2\sqrt{bd}\,\frac{\rho_A}{\rho_B\sqrt{\zeta_1}} \quad (\mathrm{cm/s^2}) \; , \qquad (2)$$

where V_H is the mean wind speed at the top of the building, b is the breadth, d is the depth of the building, ρ_A is the air density, ρ_B is the bulk mass of building per unit volume, and C_A is the revised factor that is pointed out by P.A.Irwin[4]. In this study, the C_A of 0.6 is used in comparisons between the response from the formula and the

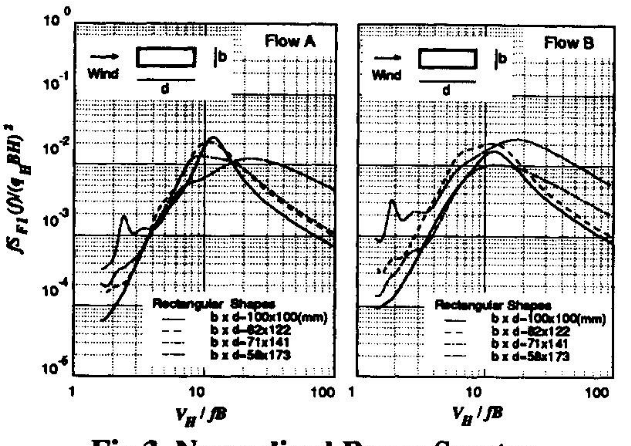

Fig.3 Normalized Power Spectra (Rectanglar Shape-A)

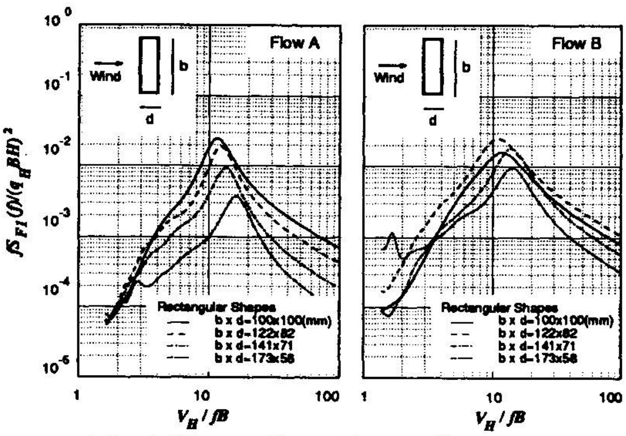

Fig.4 Normalized Power Spectra (Rectanglar Shape-B)

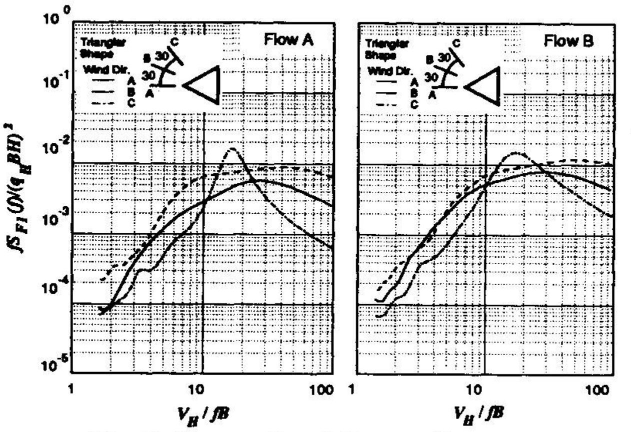

Fig.5 Normalized Power Spectra (Trianglar Shape)

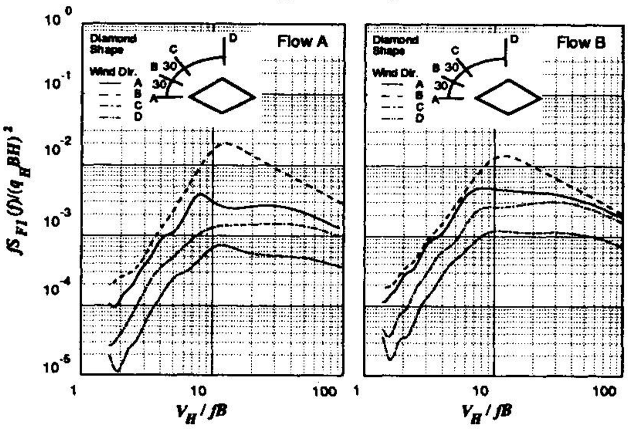

Fig.6 Normalized Power Spectra (Diamond Shape)

response based on the wind tunnel experiments.

In the investigation of the serviceability of a tall building, we must ensure that the response acceleration of the building is within the perception thresholds usually indicated as the peak acceleration value of harmonic motion. However, wind-induced accelerations of tall buildings generally are not a harmonic, but a narrow-band random process. Thus, we find the equivalent maximum acceleration corresponds to the peak acceleration of the harmonic motion by using the equivalent peak factor g_A of 2.0 to each r.m.s value from equations (1) and (2), in this study.

3. SHAPE EFFECT OF VARIOUS CROSS-SECTIONS

The relationship between the equivalent maximum acceleration and the mean wind speed V_H (> 20 m/s) at the top of the building is shown in figures 7,8,9 and 10. They show the comparisons in the equivalent maximum acceleration between the values $A^C = g_A \sigma_a{}^C$ from the revised formula in the Canadian Code and the values $A^S = g_A \sigma_a{}^S$ by the spectral modal method based on the data from wind tunnel experiments, where the r.m.s values $\sigma_a{}^S$ and $\sigma_a{}^C$ can be expressed in the equation (1) and (2), respectively. In figures 7,8,9 and 10, the characteristics of the building were

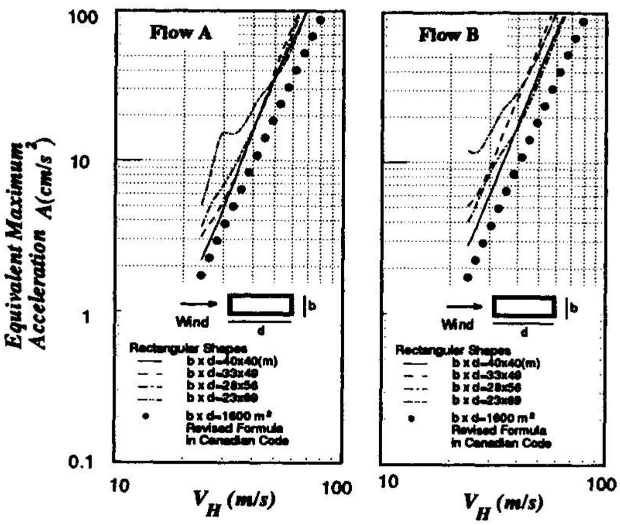

Fig.7 Equivalent Maximum Acceleration (Rectangular Shape-A)

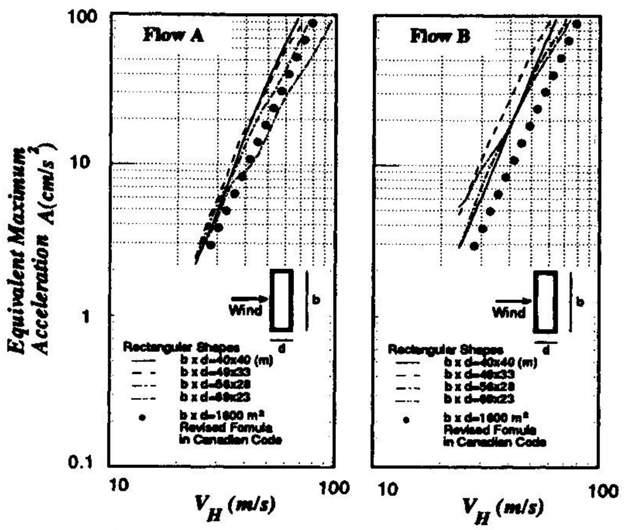

Fig.8 Equivalent Maximum Acceleration (Rectangular Shape-B)

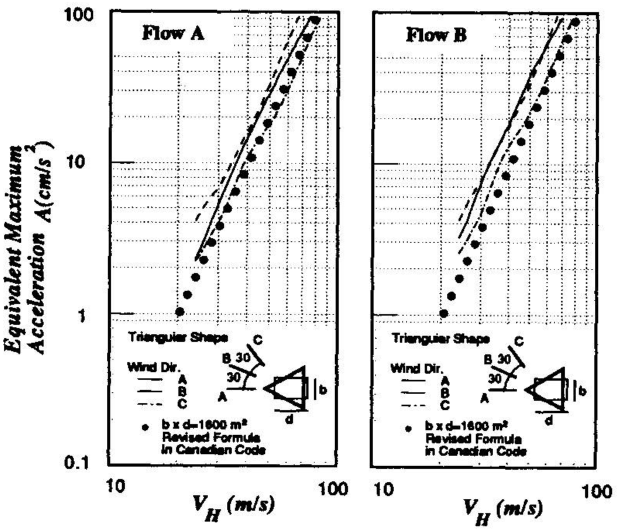

Fig.9 Equivalent Maximum Acceleration (Trianglar Shape)

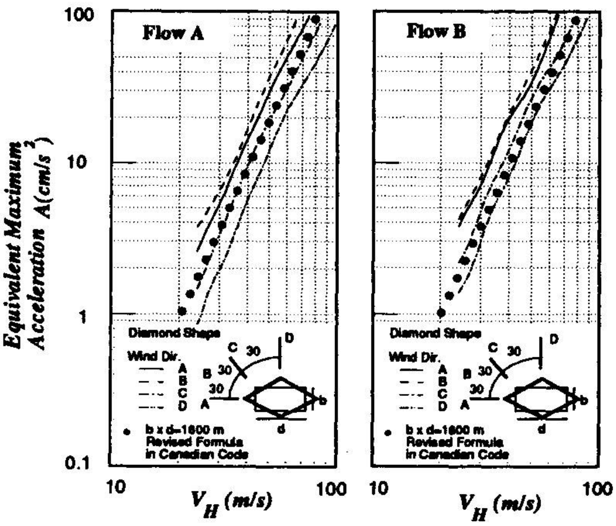

Fig.10 Equivalent Maximum Acceleration (Diamond Shape)

the following : H=160m, A $(=b\times d)$ =1600m², f_1 =0.3Hz, ζ_1 =0.01 and ρ_B =200kg/m³, for each calculation.

The accelerations A^C are less than the accelerations A^S at any wind speed V_H for each result in figures 7,8,9 and 10. The difference in both response characteristics is almost the same in the considerable range of the mean wind speed V_H. However, in the case of the rectangular section (bxd=23m x 69m), the difference between A^C and A^S becomes larger in the lower wind speed range. Thus, the formula in the Canadian Code is not suitable for the slender rectangular shape along the wind direction (for example, bxd=23m x 69m), and in turn the response characteristic from the formula differs from the characteristic by the spectral modal method based on the data from wind tunnel experiments.

From this investigation, the shape effect of the various cross sections is small in the considerable range of following the mean wind speed : 20m/s < V_H < 60m/s,

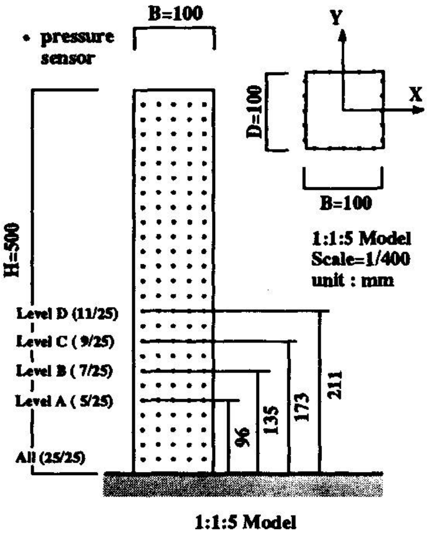

Fig.11 Presuure Model

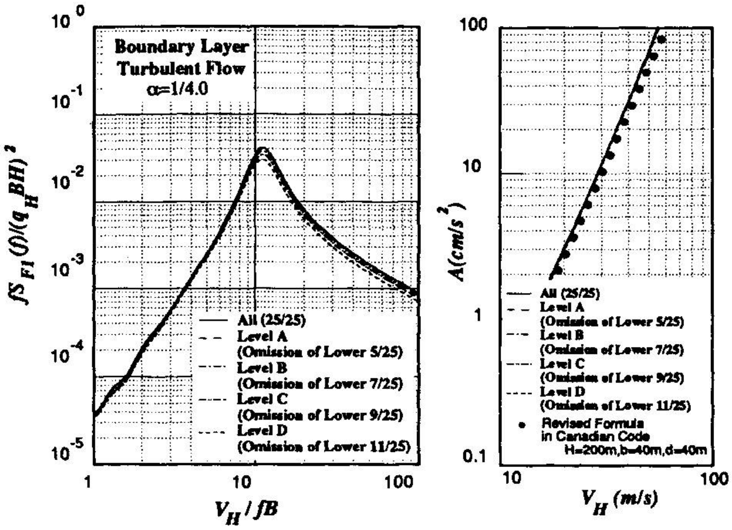

Fig.12 Effetct of the Wind Presuure Acting on the Lower Section

excluding the case of the slender rectangular shape along the wind direction. It can be also suggested that the revised factor C_A=0.6 pointed out by P.A.Irwin[4] may be small in the cross-sectional shapes that are closed with a square shape.

4. EFFECT OF LARGE LOWER SECTION

We studied the effect on the acceleration response of the large sectional area constructed at the lower part of a tall building using the pressure data from a wind tunnel experiment. The pressure model whose aspect ratio is 5 has a square cross section as shown in Fig.11. There are 25 layers of the pressure measuring section that has 5 pressure sensors in each surface of the model, making 500 pressure sensors in total. A boundary layer turbulent flow with power law exponent of 1/4 was used in the experiment.

Normalized power spectra of the generalized force $fS_{F1}(f)/(q_H BH)^2$ in an across-wind direction using the linear modal shape as the fundamental mode were calculated as shown in Fig.12. This was done under the condition that pressure measuring sections such as the lower 5, 7, 9 and 11 layers were intentionally omitted in order to study the effect of wind pressure acting on the lower part of the building. Figure 12 also shows the equivalent maximum accelerations of the building with following characteristics : H=200m, A $(=b\times d)$ =1600m^2, f_1 =0.2Hz, ζ_1 =0.01, ρ_B =200kg/m^3 and the fundamental modal shape is linear. The accelerations are calculated using the previous two methods.

From the results in Fig.12, the effect which is exerted on the accelerations by the wind pressure acting on the lower part of the building is quite small. Thus, if a large sectional area were located at the lower part of the building, the acceleration would not be influenced by the wind pressure which was distributed vertically at the lower part of the building. However, the change of the flow condition owing to the existing lower large section was not considered in this investigation.

5. COMPARISON WITH FULL-SCALE MEASUREMENT

The full-scale measurements of wind speed and response were made on the high-rise residence in Fig.13, located in the Tokyo Bay area. The building is an SRC structure with rectangular section (32m x 39m) and a height of 123.7m. From a microtremor measurement, the fundamental natural frequency is 0.43Hz, and the damping ratio of the primary mode is 1.8%. A couple of tree-cup anemometers are mounted on each side of a cross section at a level of 132m above ground. Measurements of response were carried out by accelerometers mounted at the level of 120m above ground. The records of strong winds including typhoons 9117 (Sep.14) and 9119 (Sep. 27) were obtained from the beginning of the measurements. The record of Typhoon 9119 was the strongest among them.

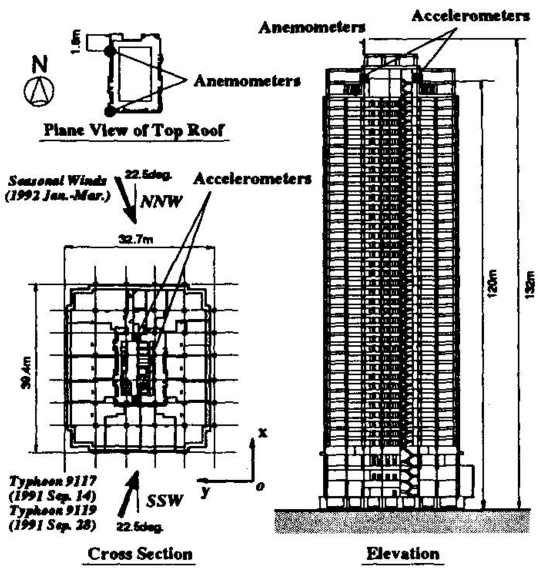

Fig.13 Cross Section and Elevation of the High-rise Residence

Figure 14 shows the mean power spectra of wind speed in Typhoon 9119. Figures 15 and 16 also show the power spectra and the time series of the response accelerations in Typhoon 9119. It was found that the acceleration in the y direction which approximated an across-wind direction was dominant and that its peak value, obtained during a 10 minutes period in which the maximum mean wind speed 23.7m/s was recorded, was 2.3cm/s². From the questionnaire investigation after Typhoon 9119, 10% of the residents who answered the questions in the higher floors felt a swaying motion, though the Typhoon passed between the time of 1:00 A.M and 3:00 A.M.

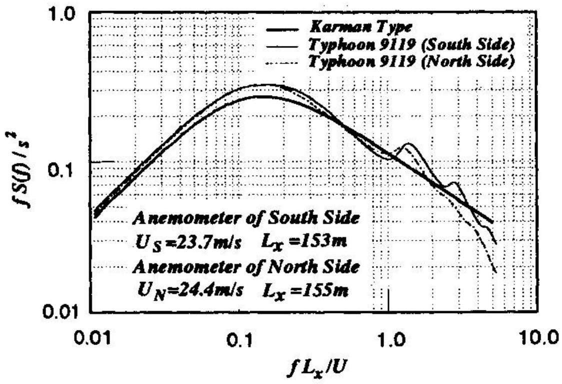

Fig.14 Power Spectra of Wind Speeds

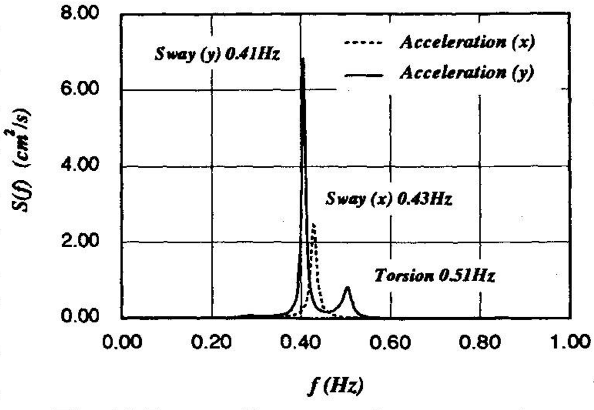

Fig.15 Power Spectra of Acceleration

Figure 17 shows the relationship between the r.m.s acceleration in an across-wind direction and the mean wind speed. The observed results in Fig.17 include the records typhoons 9117, 9119 and ordinary strong winds in the winter season. In Fig. 17, the r.m.s. accelerations from equation(2) with C_A=1.0 in the Canadian Code are also compared with measurements from the 10 minutes averaged r.m.s. accelerations.

From the result in Fig.17, the values from the formula agree with the record.

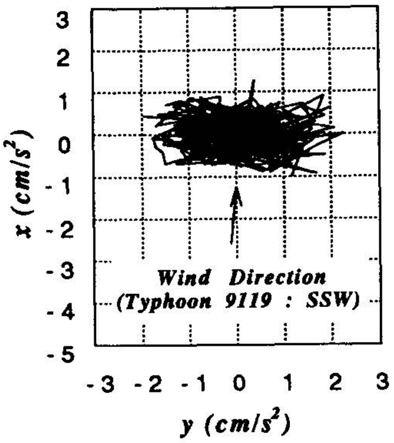

Fig.16 Time Series of Acceleration

5. CONCLUSIONS

The across-wind acceleration of tall buildings was investigated and discussed from the viewpoint of an estimation using the simple formula in the National Building Code of Canada. The main findings are briefly summarized as follows :

(1) The effect of shape of the various cross sections is small in the considerable range of the mean wind speed : 20m/s < V_H < 60m/s, excluding the case of the slender rectangular shape along the wind direction.

(2) It can be suggested that the revised factor C_A=0.6 pointed out by P.A.Irwin[4] may be small in comparison with wind tunnel experiment data in the cross-sectional shape that is similar to a square shape.

(3) The effect of wind pressure acting on the lower part of the building on the accelerations is quite small. Thus, if a large sectional area were located at the lower part of the building, the acceleration would not be influenced by the wind pressure which was distributed vertically at the lower part of the building.

(4) The values from the formula in the National Building Code of Canada agree with the records from the full-scale measurements.

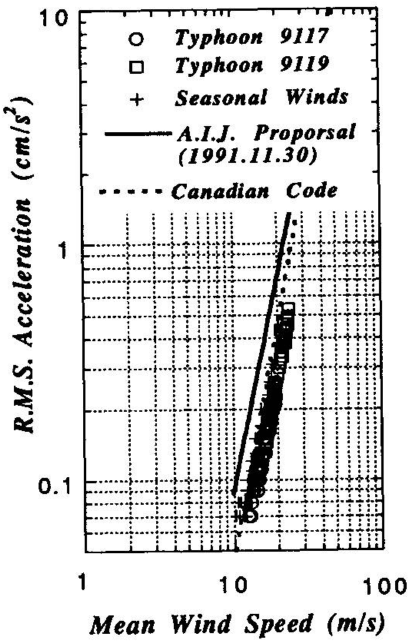

Fig.17 Comparisons with the Records from Full-Scale Measurements

Acknowledgments

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References

1. National Building Code of Canada, 1990.
2. Australian Standard,1989.
3. Agemori, Y., Choi, H. and Kanda, J. : Characteristics of Fluctuating Wind Force on 3D Cylinders, Proc. of 11th National Symposium on Wind Engineering, 1990. (In Japanese)
4. P.A Irwin : Wind Induced Motions of Building, Proc. Symposium / Work-Shop Serviceability of Buildings, Vol.1, 1988.