

Evaluation of Wind-Induced Vibration of Tall Buildings and Reliability Analysis: A Case Study

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The alongwind, crosswind and torsional components of wind forces are simultaneously measured during a wind tunnel test of a rigid model of a tall building. The three components of wind-induced responses of the tall building are thus estimated and investigated by structural dynamic analysis. A reliability assessment procedure is presented in terms of upcrossing probabilities of wind-induced response and provides a convenient checking procedure for serviceability performance evaluation of tall buildings under stochastic wind loads.

Keywords: Wind Loading, Wind-Induced Vibration, Tall Building, Reliability Analysis, Wind Tunnel Test

Introduction

The oscillations of tall buildings caused by wind action have been found to occur in the alongwind and crosswind directions as well as torsional mode. While several procedures, e.g., gust factor approach, have been developed for predicting loads and response in alongwind direction, very few procedures (e.g., National Building Code of Canada, Australia Standard) are available for evaluating crosswind or torsional load and response. This lack of guidance may be significant because crosswind force and response may be considerably larger than alongwind force and response for certain cases (Li et al. 1998a, 1998b). Also due to the fact that the torsional motion is discernible at a much lower level of response than the translational motions, the torsional effects may be more readily perceived by occupants (Kareem 1985). Therefore, it is essential to require knowledge of wind-induced alongwind, crosswind and torsional responses of tall buildings.

For modern flexible and lightly damped buildings, serviceability issues are of paramount importance and occupant comfort is a major concern in the design of tall buildings. There are uncertainties inherent in the wind environment and structural properties as well as parameters reflecting wind-structure interactions which can be adequately defined only by means of statistics. Therefore, wind-related serviceability issues should be evaluated in terms of structural reliability analysis. Structural reliability assessment under alongwind load has been investigated by several authors (e.g., Li and Cao 1986). Kareem (1990) presented a reliability analysis of tall reinforced-concrete chimneys under combined alongwind and crosswind loads. However, the reliability analysis of structures under combined stochastic alongwind and crosswind as well as torsion loads has received little attention in the literature in the past.

In this study, wind-induced vibration of a typical tall building is investigated. Reliability analysis (from an occupant-comfort point of view) of the tall building under combined stochastic wind loads including alongwind, crosswind, and torsional components is presented in terms of upcrossing probabilities. The reliability that a particular response component of the building will be exceeded a specified level can be predicted. Lifetime reliability evaluation is fully realized when the response estimates are integrated with statistics of local meteorological variables.

Wind-Induced Responses

This paper presents a case study on the evaluation of wind-induced vibration and reliability analysis of a typical 30-storey steel tall building having dimensions 40m x 40m x 120m and an average mass density of 187.5 kg/m³. As discussed previously, in the absence of analytical procedures, lift, drag and torsional forces usually should be determined by wind tunnel test.

The wind tunnel test was conducted employing a boundary layer wind

tunnel of 1.6 x 2.0m in the measuring section, which is the property of Kajima Corporation. Dimensions of the 1:400 model in the wind tunnel test are 0.3m high, 0.1m width and length. The approach wind was simulated for flow over open terrain as recommended by the Wind Code of China.

The experimental model and the location of pressure taps should be referred to Fig.1. The model was divided into ten levels at various heights. A pressure tap was 1mm in diameter and normal to the model face. The model was instrumented on four faces. At each level, ten and eleven point pressures were monitored on either face for estimating normal forces and twisting moments, respectively. Multi-tube system with manifolds was used for the measurements of wind pressures in the wind tunnel test. Horizontal wind forces (including alongwind and crosswind forces) and twisting moments were measured simultaneously at five levels, respectively and recorded for the duration of four seconds and about 1000 samples per second data were included at each pressure tap. The total 4099 samples for each wind force component at every measuring level along the test model were obtained and used in this study. Li (1990) gave a detailed introduction on the instrumentation of the model in the wind tunnel test.

The information on the mean and fluctuating wind forces on the building model measured in the wind tunnel test can be used to estimate the dynamic response of this building by structural dynamics analysis. Assume that the building can be modeled as a multi-degree-of-freedom system having two perpendicular translational motions and one rotational movement, and behaves elastically at service load levels. Fig.1 shows

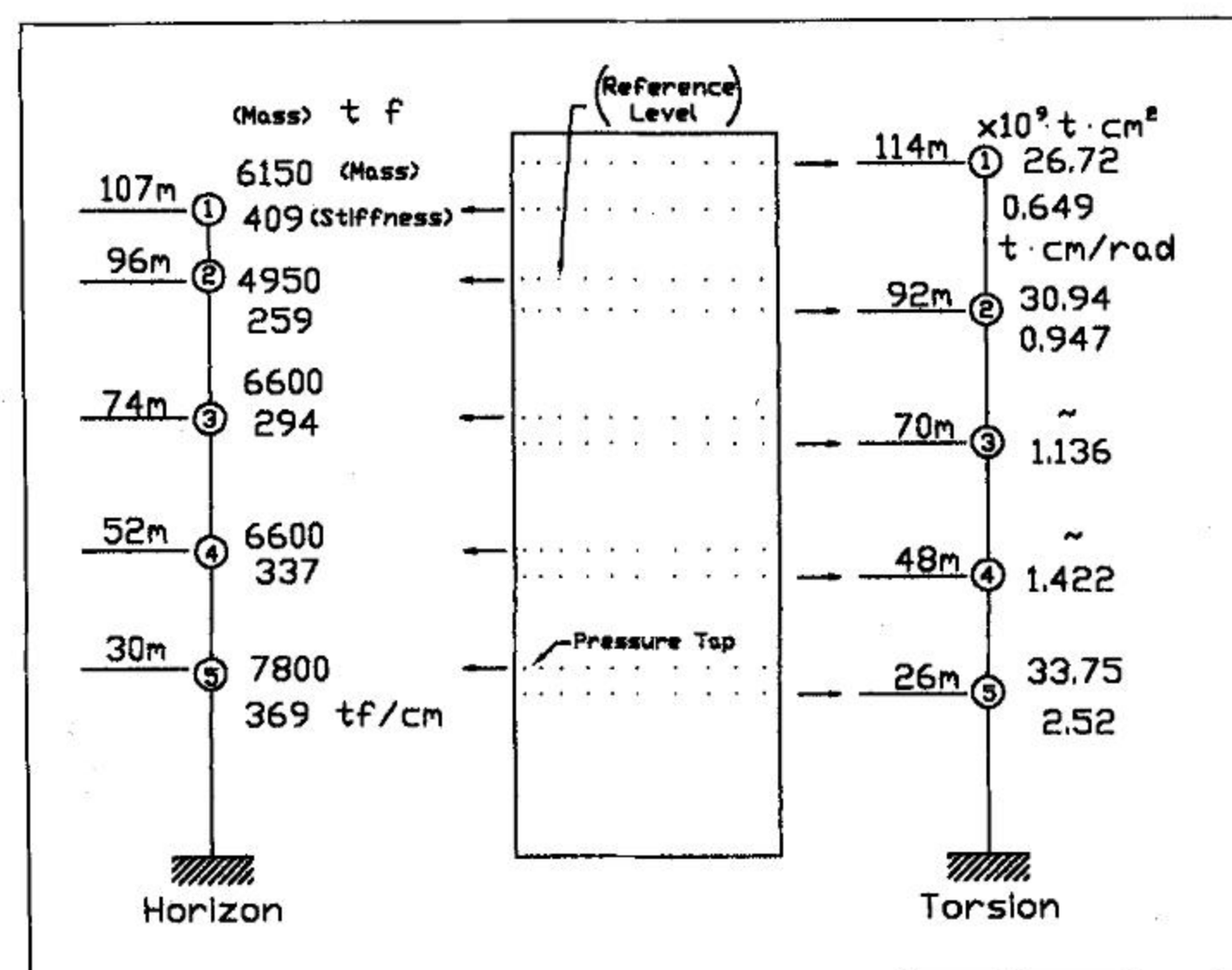


Figure 1 – The Experiment Model and Analytical Model

the analytical model and structural parameters of the tall building. Based on the full-scale measurements of damping in typical tall buildings (Fang et al. 1998, Fang et al. 1999, Li et al. 1998a), the first mode damping ratios were reasonably assumed to be 1% in the three directions. According to the structural parameters presented in Fig.1 and structural dynamics theory (e.g., Li et al. 1994, 1996), the first mode natural periods of horizontal and torsional components were calculated as 3.00 and 2.99 seconds, respectively.

As mentioned above, the tall building was discretized by a lumped mass idealization. Each lumped mass point of the analytical model was inputted the corresponding three component wind forces which have been measured from the wind tunnel test. The responses of the tall building under the combined stochastic wind loads were calculated by using the Newmark- β method.

The wind-induced responses of the tall building were calculated while the wind velocity at the top of the building varied from 10m/s to 100m/s. The calculated results include displacement, velocity, acceleration components in the three principal directions. The torsional response in the figures presented in this paper is represented as a translational response at the center of the building side. In Fig.2 and 3, the rms response values at the top floor of the building were plotted as a function of reduced

velocity $\frac{V_H}{fD}$, in which V_H is the mean wind speed atop the building, f

is the fundamental translational natural frequency and D is the width of the cross section of the building, respectively. The results calculated in accordance with the National Building Code of Canada were also presented in Fig.2 for comparison purposes. The predicted response values in crosswind motion show good agreement with the values computed in terms of the Code. The predicted results demonstrate that the standard deviation of acceleration is proportional to 2.7 powers of wind velocity at the building top in alongwind and to 3.3 powers in crosswind, as well as to 2.5 powers in torsional direction. The crosswind response of the tall building can be very large, especially while the speed is strong, and should be considered in design. Ignoring this important component, overall wind-induced response may be significantly underestimated. The

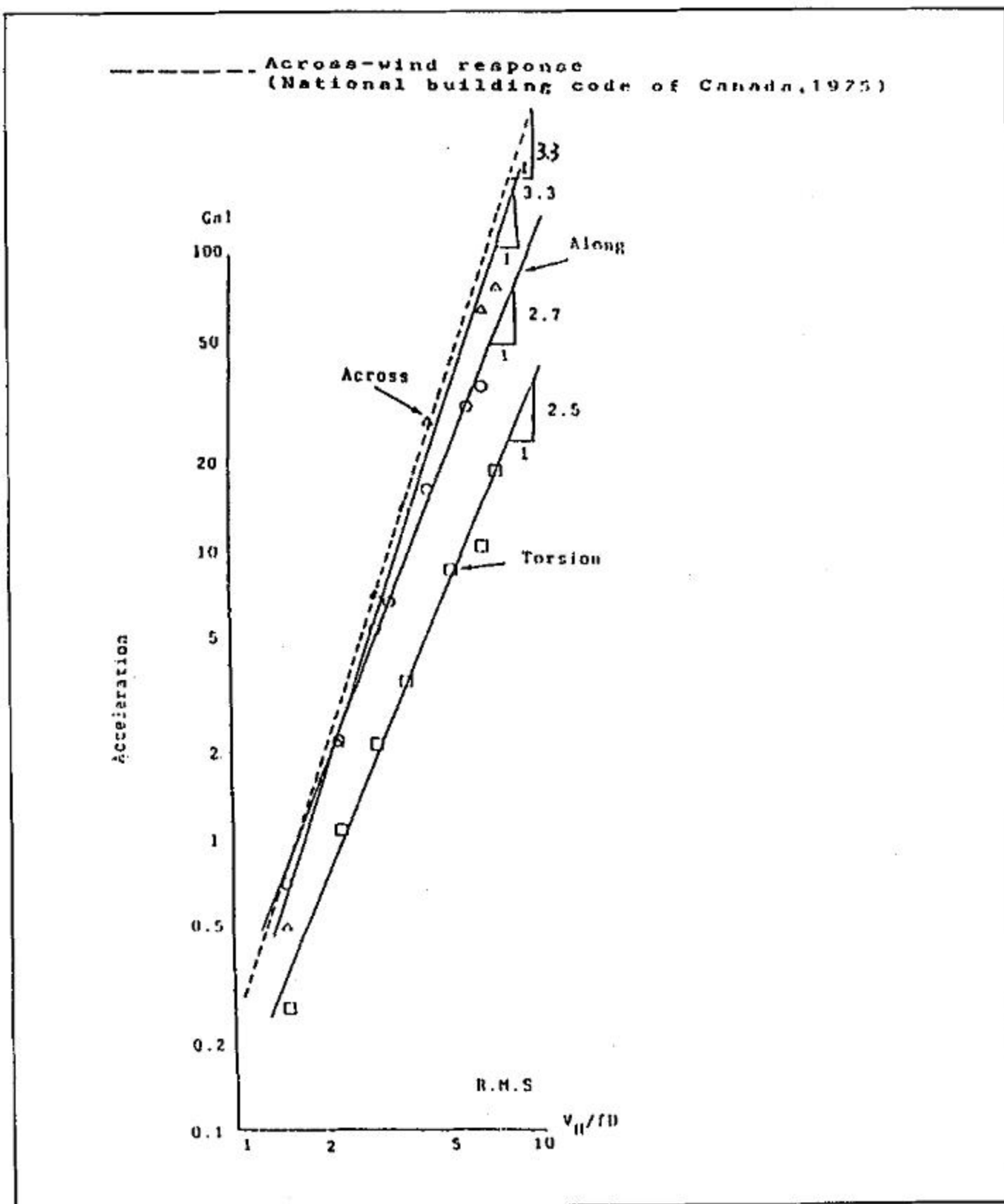


Figure 2 – Distribution of Acceleration Responses at the Top Floor

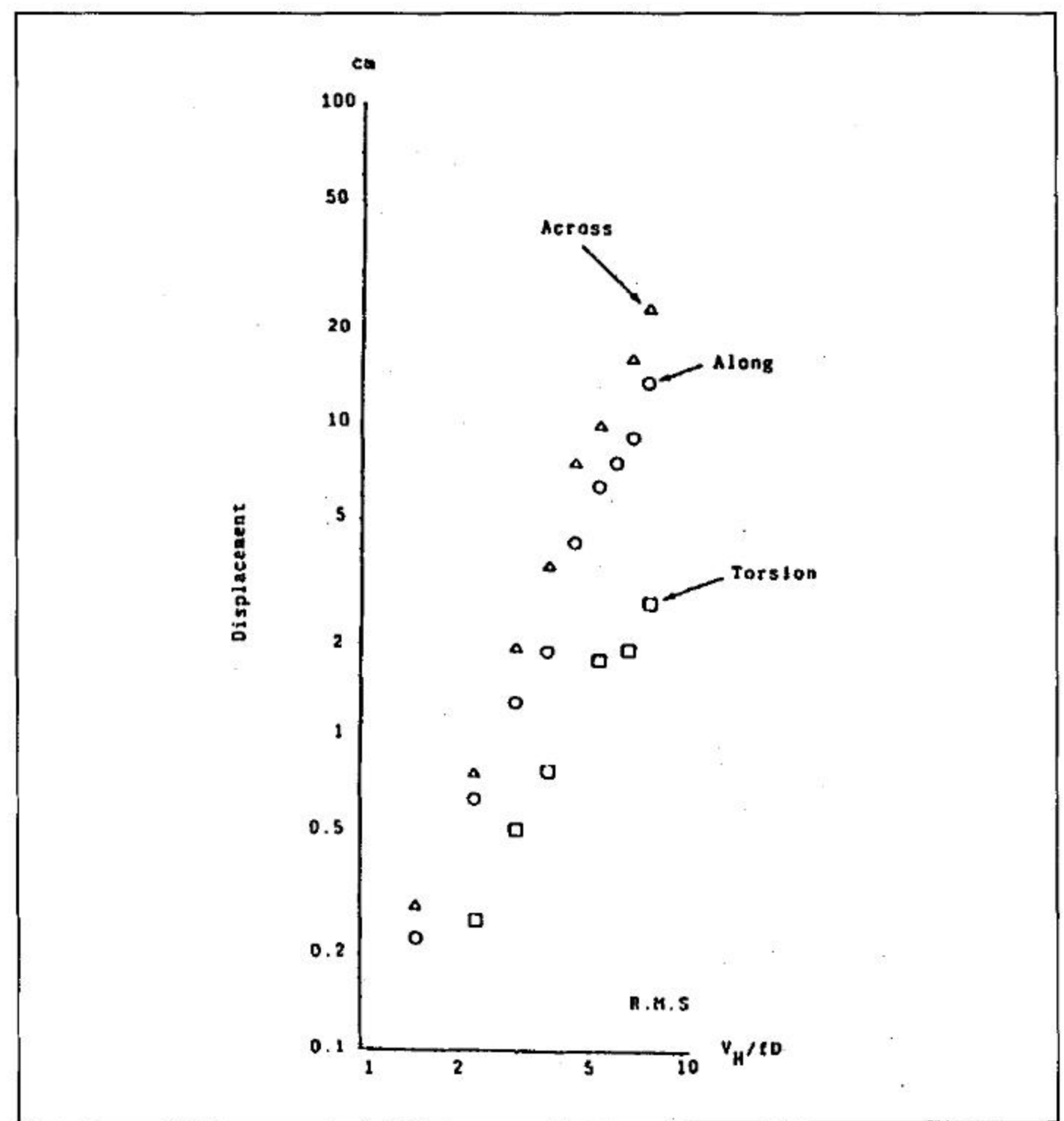


Figure 3 – Distribution of Displacement Responses at the Top Floor

dominance of the crosswind vibration at high reduced velocities is due to the high concentration of energy in its force spectra near the Strouhal number (Li 1990). The calculated results in Figs.2 and 3 also show that even a perfectly symmetric building with normally incident wind experiences significant torsional motion. Due to the fact that the torsional motion can be often perceived by a visual-vestibular mechanism at motion thresholds that are an order of magnitude smaller than those for lateral transitory motion (Kareem 1985), the torsional effects on human discomfort near tall building corners at top floors need to be considered for design purposes.

Reliability Analysis

The structural reliability analysis generally includes structural safety and serviceability assessment. It has been widely accepted that building acceleration is the most appropriate response component for establishing checking procedure for structural serviceability requirements under wind action. It is often the serviceability limit state that governs the design of tall buildings under wind action. Reliability analysis presented in this paper is restricted to serviceability assessment by means of the evaluation of acceleration responses, which can be extended for other risk prediction associated with various safety and serviceability criteria such as structural strength and deflection etc.

The upcrossing probability of wind-induced acceleration of the tall building was performed by digital analysis based on the time domain response results. The typical upcrossing probabilities obtained are shown in Fig.4 and the results can be used to determine the variations from that of a normally distributed process. Fig.4 shows that at the case of $V_H = 40\text{m/s}$, the alongwind, crosswind and torsional acceleration responses atop the building are essentially normally distributed. Thus, in order to simplify the reliability analysis, the total combined acceleration is assumed as a normal distribution herein.

The lifetime failure probability of a wind-excited structure can be expressed as

$$P_f(T) = \int_0^{\infty} P(R < S/V = v) f_T(v) dv \quad (1)$$

where T = design lifetime, usually 50 years; $P_f(T)$ = lifetime failure

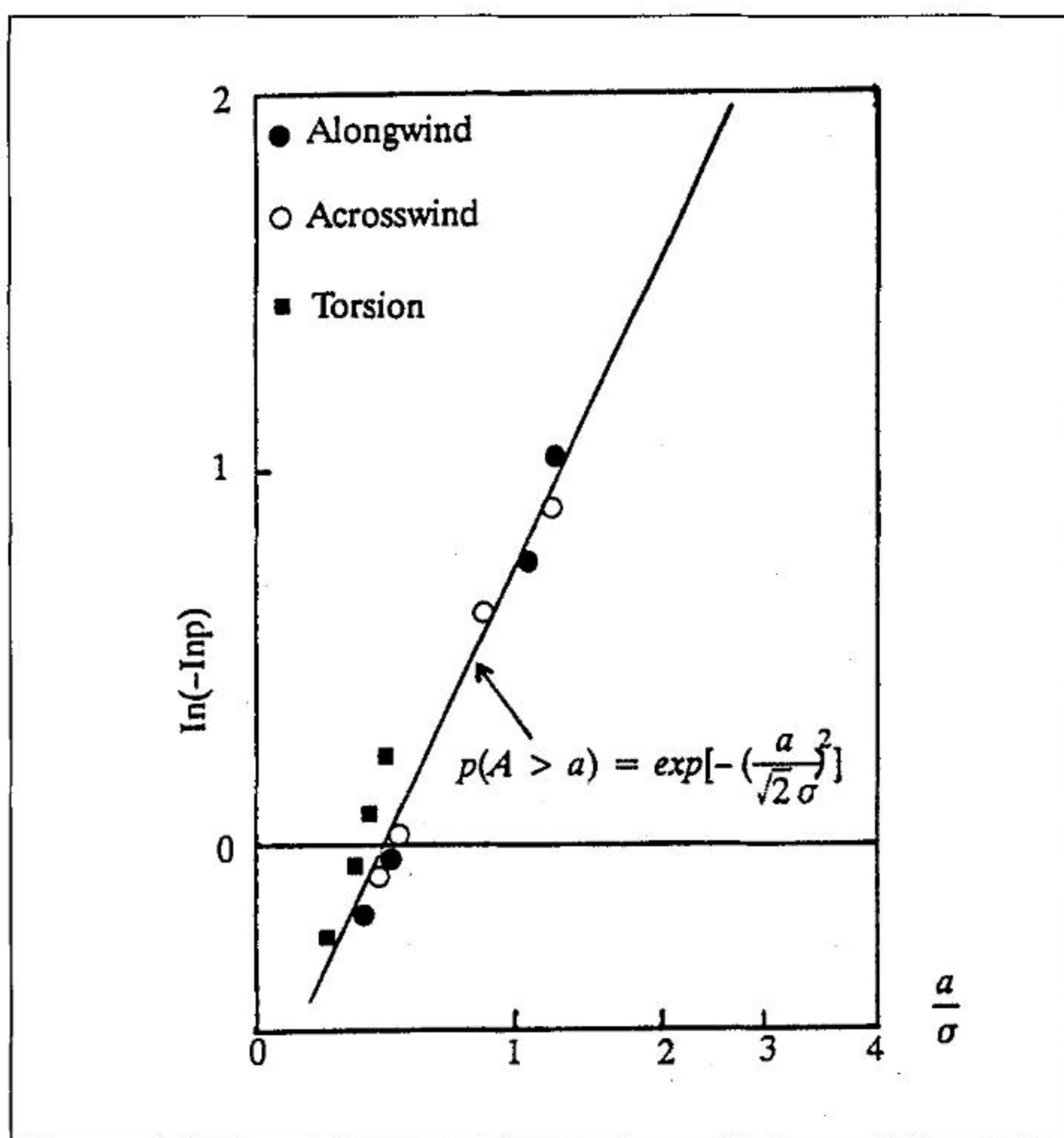


Figure 4 – Upcrossing Probabilities for Acceleration Responses

probability; $f_T(v)$ = probability density function of maximum wind speed in the T years; S = response quantity of interest, acceleration response in this paper; R = the corresponding structural resistance; $P(R < S/V = v)$ = the conditional probability of failure given $V = v$.

Eq.1 can be written in a discrete form so that it is convenient for calculation.

$$P_T(T) = \sum_i P(R < S/V = v_i) [F_T(v_i) - F_T(v_{i-1})] \quad (2)$$

in which $F_T(v)$ = probability distribution function of the maximum wind speed in the T years, which can be derived from a statistics analysis of successive years of climatological data.

Analysis of data at various locations with well-behaved wind climates has suggested that the extreme value Type I distribution in general provides a good fit to the extreme yearly wind speed data (Li and Cao 1986). Assuming that yearly maximum wind speeds over a period of T years are independent. For example, at the case of the extreme Type I distribution, The probability density function of the T year extreme wind speed can be expressed as

$$f_T(v) = T\alpha \exp\{-(v-\alpha)\beta\} - T \exp[-(v-\alpha)\beta] \quad (3)$$

in which α and β can be estimated from a sizable sample of annual extreme mean wind speed data by the method of moments.

A number of proposals and regulations for limitation of wind-induced vibration have been suggested. Some codes, for example, the National Building Code of Canada suggests acceptable levels of accelerations as a serviceability requirement, which recommends that a tentative acceleration limitation of 1 to 3 percent of gravity once every 10 years as a guideline for comfort of occupants and the lower value might be considered appropriate for apartment buildings, the higher value for office buildings. Thus, the peak acceleration values of 1%g and 3%g were taken as the serviceability threshold to evaluate the reliability of wind-excited tall building herein.

The conditional probabilities of unserviceability due to excessive acceleration at the corner of the top floor of the building associated with alongwind, crosswind and total wind load effects including the torsional load are given in Fig.5. There is a significant difference between the first and second cases while the wind speed is strong, which is attributed

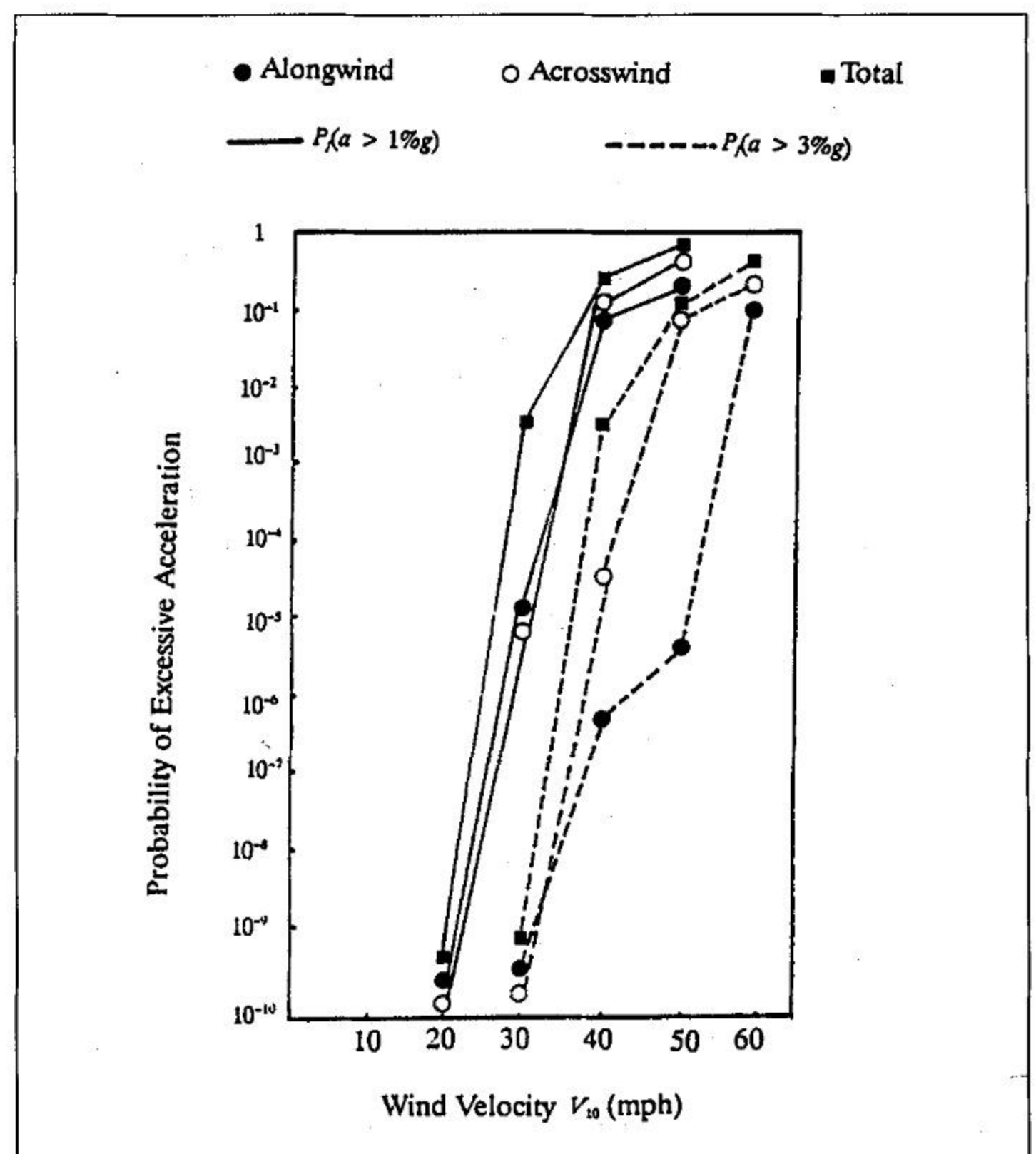


Figure 5 – Probability of Excessive Acceleration

to the predominance of crosswind response in the range of higher wind velocity. Therefore, the probability of unserviceability may be seriously underestimated by ignoring crosswind response. It is also noteworthy that the value of serviceability threshold has a significant effect on the probability of unserviceability.

The lifetime probability of failure (unserviceability) can be obtained from the conditional probability of failure (unserviceability) through convolution with the lifetime extreme wind distribution. In this study, the extreme value Type I, Type II and Lognormal distributions were employed to model the annual maximum wind speed distribution. Because the tall building considered in this paper is located in Wuhan, P.R. China, the parameters of the distributions were determined from 20 years of available wind speed data in Wuhan, which had been obtained from the local meteorology reference. The averaging time for the maximum mean wind speed in this analysis was 10 minutes. The mean and standard deviation of annual maximum wind speed at 10m above the ground were calculated as $V = 19.0\text{m/s}$, $\sigma = 2.52\text{m/s}$, respectively. The lifetime (50 years) probability of failure of the tall building are summarized in Table 1.

The Lognormal distribution has the shortest tail while the extreme value Type II has the flattest shape with the longest tail. The results in Table 1 suggest some dependence of the probability of failure on the form of the extreme wind speed distribution, and the Type II distribution gives the highest probability of failure, followed by Type I and Lognormal distributions. The results based on the different distributions all again reveal that the crosswind response has a significant effect on the probability of unserviceability of the tall building under wind action.

Concluding Remarks

Based on the simultaneously measured alongwind, crosswind and torsional wind loads on a tall building model in wind tunnel test, the corresponding wind-induced responses of the building were estimated and investigated by structural dynamics analysis. The results obtained in this study show that the standard deviation of acceleration is proportional to 2.7 powers of wind velocity at the building top in alongwind and to 3.3 powers in crosswind, as well as to 2.5 powers in torsional direction. The crosswind response of the tall building can be very large, especially while the speed is strong, and should be considered in design. It has been found that

Probability of Failure	Type I			Type II			Lognormal		
	Along	Cross	Total	Along	Cross	Total	Along	Cross	Total
P(A>1%g)	0.1648	0.3194	0.4544	0.2011	0.3753	0.5123	0.1529	0.2829	0.4280
P(A>3%g)	0.0003	0.0061	0.0124	0.0063	0.0277	0.0408	0.0001	0.0004	0.0036

Table 1 – Lifetime Probability of Failure Due to Exceeding of Acceleration

even a perfectly symmetric building with normally incident wind experiences significant torsional motion, and the torsional response near the corner in the tall building can be of the same order as alongwind and crosswind responses. The importance of the torsional response should be emphasized due to the fact that the torsional motion is discernible at a much lower level of response than the translational motions.

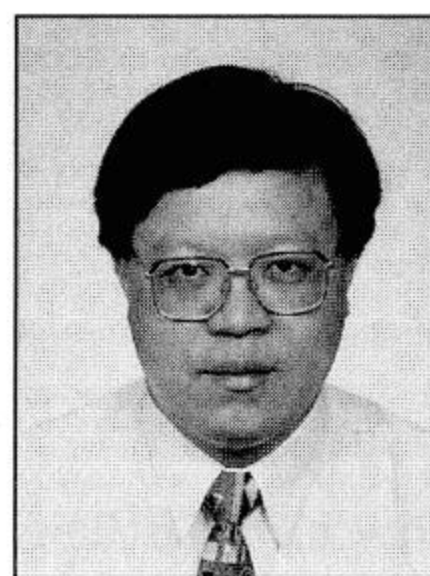
A practical probabilistic procedure is presented in terms of upcrossing probabilities of wind-induced response and provides a convenient checking procedure, from structural reliability viewpoint, which combines the features of wind tunnel derived alongwind, crosswind and torsional components of wind forces acting on the tall building and the evaluation of the corresponding wind-induced vibration as well as the analysis of probability distributions of response. The probability distributions of upcrossing show that alongwind and crosswind as well as torsional motions are similar to the normally-distributed process, and the crosswind response has a significant effect on the probability of unserviceability of the tall building under stochastic wind action. The lifetime probability of unserviceability of the tall building seems to be high and low corresponding to the serviceability threshold taken as 1%g and 3%g, respectively. From the results of this study, and from an occupant-comfort point of view, it is recommended that this tall building should be more suitable to be used as an office building at the top floors.

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Dr Li obtained his PhD from Monash University, Australia. Before joining City University as an academic staff in 1996, Dr Li had seven years of working experience as a research engineer at Kajima Corporation in Japan and a consultant in MEL Consultants Pty Ltd in Australia. During this period, he had been involved in numerous wind engineering studies on major building and structural developments both in Australia and overseas. His main research interests and technical expertise are in structural dynamics, wind engineering, structural engineering, computational fluid and solid mechanics, reliability and risk assessment. Over the last sixteen years, Dr Li's research on these fields has resulted in over 50 referred international journal papers. He is a co-author of two books on structural dynamics and earthquake engineering. Dr Li received the Professor K H Hunt Award for excellence in research in 1997. He is the editorial board member of three journals. Currently, Dr Li is a principal investigator for six research grants with a total funding over HK\$1.5 million.