Reliability Analysis of High-Rise Buildings under Wind Loads

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Abstract: The objective of this paper is to conduct the reliability analysis of high-rise buildings under wind loads. Numerical examples are provided to capture the dynamic effects of structures with eccentricity between the elastic and mass centers. The framework of this research consists of two stages. The first stage includes two parts: the deterministic analysis of wind-induced acceleration for a variety of attack angles, i.e., the demand, and the determination of allowable acceleration based on the occupant comfort criteria for wind-excited buildings, i.e., the capacity. According to the results obtained in the first stage, the reliability analysis is conducted in the second stage, which can predict the probability of dissatisfaction with occupant comfort criteria for a variety of probability distributions of the structural eccentricity. The findings indicate that, compared to the lognormal and type I extreme value distributions, the normal distribution can be used to more conservatively simulate the uncertainties of the eccentricity between the elastic and mass centers. Furthermore, the probability of dissatisfaction with occupant comfort criteria of the torsionally coupled system is relatively higher than that of the torsionally uncoupled system for each attack angle due to the coupled mode effects.

Keywords: Reliability analysis, High-rise building, Wind load, Elastic center, Attack angle

1. Introduction

Traditionally, structural analysis is based on deterministic approaches, i.e., each parameter of analytical model is considered to be a certain value. In fact, uncertainties exist in design, construction, operation and maintenance of real structures. Consequently, traditional analysis is not able to effectively capture structural properties. On the basis of probabilistic approaches, reliability analysis is used to simulate probability distribution of each parameter, implying that uncertainties can be reasonably modeled by such method. This fact indicates that reliability analysis is a more appropriate tool than traditional analysis. In Taiwan, both structural safety and occupant comfort of high-rise buildings have become important due to frequent typhoons, implying that wind hazard is a significant factor for design purposes. Uncertainties of both wind loads and high-rise buildings have to be considered for structural design. From the above description, reliability analysis is useful for exploring the problem of high-rise buildings under wind loads.

The objective of this paper is to conduct the reliability analysis of high-rise buildings under wind loads. Numerical examples are provided to capture the dynamic effects of structures with eccentricity between the elastic and mass centers. The framework of this research consists of two stages, as shown in Figure 1. The first stage includes two parts: the deterministic analysis of wind-induced acceleration for a variety of attack angles, i.e., the demand, and the determination of allowable acceleration based on the occupant comfort...
criteria for wind-excited buildings, i.e., the capacity. According to the results obtained in the first stage, the reliability analysis is conducted in the second stage, which can predict the probability of dissatisfaction with occupant comfort criteria for a variety of probability distributions of the structural eccentricity.

Figure 1. Framework of the research.
2. High-Rise Building Model

An $N$-story torsionally coupled system is used to simulate a high-rise building, and its corresponding three-dimensional configuration and top view of the $i$th floor are illustrated in Figure 2(a) and 2(b), respectively\(^1\), where $x$, $y$, $z$ and $\theta$ are the coordinates of the system; $D_i$, $B_i$, $H_i$ and $Z_i$ are the depth, breadth, height and elevation, respectively; $MC_i$, $EC_i$ and $AC_i$ are the mass, elastic and aerodynamic centers, respectively; $Ex_i$ and $Ey_i$ are the eccentricities between $EC_i$ and $MC_i$ in the $x$ and $y$ axes, respectively; $Ax_i$ and $Ay_i$ are the eccentricities between $AC_i$ and $MC_i$ in the $x$ and $y$ axes, respectively.

Several assumptions are adopted in this study: (1) each rigid diaphragm with three degrees of freedom $x$, $y$ and $\theta$ is characterized by the mass $M_i$ and the moment of inertia $I_i$ about $MC_i$; (2) each massless column is characterized by $Kx_i$, $Ky_i$ and $K\theta_i$, which individually denote the stiffnesses in the $x$, $y$ and $\theta$ axes referred to $EC_i$; (3) wind loads are applied at $AC_i$; (4) $MC_i$, $EC_i$ and $AC_i$ are non-coincident, and $MC_i$ is located in the centroid of the diaphragm; (5) the Rayleigh damping with the mass-related coefficient $A_0$ and the stiffness-related coefficient $A_1$ is used. The model in Figure 2 can be simplified to an $N$-story torsionally uncoupled system when $Ex_i$ and $Ey_i$ both equal zero.

The procedure for the modeling of high-rise buildings is summarized in Figure 1. Based on the parameters mentioned above, the mass, stiffness and damping matrices of the system can be generated, and the frequency response function of acceleration can therefore be obtained (Kan and Chopra, 1977; Yang et al., 1981; Samali et al., 1985; Kareem, 1985; Kareem, 1992; Wu and Yang, 2000; Liu et al., 2008).

3. Wind Load Model

Wind loads can be decomposed into an average, aerodynamic damping and fluctuation terms. The fluctuation term is considered and the other two terms are neglected, which can be used to appropriately conduct the dynamic analysis under the assumption of small deformation theory. The wind load components including the drag, lift and torque are illustrated in Figure 3, where the attack angle $\phi$ is defined as the angle between the wind direction and the $x$ axis. The drag and lift both act through $AC_i$, where the former and the latter are parallel and perpendicular to the wind direction, respectively. The torque is due to the eccentricity between $AC_i$ and $MC_i$. The drag, lift and torque can be written as a function of $\phi$ (Yang et al., 1981; Samali et al., 1985; Wu and Yang, 2000; Simiu and Scanlan, 1996; Peng, 2005).

The procedure for the computation of wind loads is summarized in Figure 1. According to the power law, the wind velocity profile showing the variations in the mean wind velocity over the elevation can be expressed as a function of the exponent $\alpha$, the gradient height $Z_g$ and the gradient wind velocity $V_g$ (Simiu and Scanlan, 1996). Based on the wind velocity profile, the reference mean wind velocity at 10 m above the ground $V_s$, the ground roughness coefficient $K_s$ and the exponential decay coefficient $C_i$ are used to calculate the cross-spectral density function of wind velocity between two elevations (Davenport,

\(^1\) The subscript $i$ in Figure 1 represents the parameter of the $i$th floor in this research.
By combining both the wind velocity profile and cross-spectral density function of wind velocity, the cross-spectral density function of wind load between two axes can be obtained by the air density $\rho$, the windward side area of floor, the mean wind velocity, the drag coefficient $C_D$, the lift coefficient $C_L$, $Ax_i$ and $Ay_i$ for a variety of $\phi$ (Yang et al., 1981; Samali et al., 1985; Wu and Yang, 2000).

![Diagram of a three-dimensional configuration](image)

![Diagram of top view of the i-th floor](image)

*Figure 2. N-story torsionally coupled system.*
4. Demand and Capacity

As shown in Figure 1, the deterministic analysis of wind-induced acceleration of structures with eccentricity between $EC_i$ and $MC_i$ for a variety of $\phi$ is conducted from the high-rise building and wind load models. The computational procedure is based on the frequency domain analysis. By combining both the frequency response function of acceleration and cross-spectral density function of wind load, the cross-spectral density function of acceleration between two axes, and the corresponding root-mean-square acceleration at mass center and that at corner can be calculated (Kareem, 1985; Kareem, 1992). The peak acceleration at corner, i.e., the demand, then can be obtained by multiplying the response at mass center by the peak factor (Melbourne, 1977).

The allowable peak acceleration of structures, i.e., the capacity, can be determined based on the occupant comfort criteria for wind-excited buildings. The threshold can be written as a function of the frequency of structural oscillation $F$, the duration of wind velocity $T$ and the return period of wind velocity $R$ (Melbourne and Palmer, 1992).

5. Reliability Analysis

According to the demand and capacity for different attack angles obtained in the first stage, the reliability analysis of high-rise buildings under wind loads based on the synthetic method combining both the Rackwitz-Fiessler and finite difference methods is conducted in the second stage, which can predict the
design point, reliability index and probability of dissatisfaction with occupant comfort criteria for a variety of probability distributions of the structural eccentricity, as shown in Figure 1.

The basic variables \( X_i \) (\( i = 1, 2, \ldots, n \)) and the corresponding limit state function \( Z = g(X_1, X_2, \ldots, X_n) \) are the essences of reliability analysis. \( X_i \) (\( i = 1, 2, \ldots, n \)) can be used to simulate the uncertainties of \( n \) parameters in a system. \( Z \) is the standard to judge whether each performance criterion is satisfied in the system. Figure 4(a) illustrates the relationships between \( Z \) and \( X_i \) (\( i = 1, 2, \ldots, n \)) in the original coordinate system. The limit state \( (Z = 0) \) is the boundary between the safe region \( (Z > 0) \) and the unsafe region \( (Z < 0) \). \( X_i \) (\( i = 1, 2, \ldots, n \)) can be transformed to the standard normal variables \( X'_i \) (\( i = 1, 2, \ldots, n \)), respectively, and the corresponding limit state function \( Z = g(X'_1, X'_2, \ldots, X'_n) \) can therefore be determined. The relationships between \( Z \) and \( X'_i \) (\( i = 1, 2, \ldots, n \)) in the transformed coordinate system are illustrated in Figure 4(b). The safe region \( (Z > 0) \) and the unsafe region \( (Z < 0) \) are divided by the limit state \( (Z = 0) \) similar to Figure 4(a). The design point \( (x'_1*, x'_2*, \ldots, x'_n*) \) is located in \( Z = 0 \) closest to the origin. The reliability index \( \beta \) with the distance between the design point and the origin is a useful index for assessing the system reliability. The probability of dissatisfaction with occupant comfort criteria \( p_f \) can be expressed as a function of \( \beta \) (Haldar and Mahadevan, 2000a; Haldar and Mahadevan, 2000b).

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\[ Z = g(X_1, X_2, \ldots, X_n) \]

**Basic variable**

\[ Z < 0 \]

Unsafe region

\[ Z = 0 \]

Limit state

\[ Z > 0 \]

Safe region

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**Basic variable**

\[ Z = g(X'_1, X'_2, \ldots, X'_n) \]

**Limit state function**

\[ Z = 0 \]

Unsafe region

\[ Z > 0 \]

Safe region

---

**Design point**

\( (x'_1*, x'_2*, \ldots, x'_n*) \)

**Reliability index**

\( \beta \)

---

\( \text{Figure 4. Relationships between the limit state function and the basic variables.} \)

The Rackwitz-Fiessler method contains the parameters in both the original and transformed coordinate systems. The algorithm is formulated as follows (Rackwitz and Fiessler, 1978):

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2 The parameters marked with asterisk represent the ones based on the design point in this research.
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Step 1. $Z$ is defined.

Step 2. The initial value for each component of the design point in the original coordinate system $x_i^* (i=1,2,\cdots,n)$ is given. These values are assumed to be $\mu_{x_i} (i=1,2,\cdots,n)$ representing the mean values of $X_i (i=1,2,\cdots,n)$, respectively. The corresponding initial value of $g(x_1^*,x_2^*,\cdots,x_n^*)$ can therefore be determined.

Step 3. For the non-normal variables in $X_i (i=1,2,\cdots,n)$, both their mean values and standard deviations of the equivalent normal variables, i.e., $\mu^N_{x_i}$ and $\sigma^N_{x_i} (i=1,2,\cdots,n)$, respectively, can be estimated based on the Rackwitz-Fiessler transformation (Rackwitz and Fiessler, 1976). $x_i^* (i=1,2,\cdots,n)$ then can be calculated as

$$x_i^* = \frac{x_i^* - \mu^N_{x_i}}{\sigma^N_{x_i}}. \quad (1)$$

Step 4. $\left(\frac{\partial g}{\partial x_i^*}\right)^* (i=1,2,\cdots,n)$ are calculated.

Step 5. $\left(\frac{\partial g}{\partial x_i^*}\right)^* (i=1,2,\cdots,n)$ can be calculated as

$$\left(\frac{\partial g}{\partial x_i^*}\right)^* = \left(\frac{\partial g}{\partial x_i^*}\right)^* \sigma^N_{x_i}. \quad (2)$$

Step 6. $x_i^* (i=1,2,\cdots,n)$ can be modified by the recursive formula

$$\text{New}(x_1^*,x_2^*,\cdots,x_n^*) = \sum_{i=1}^{n} \left(\frac{\partial g}{\partial x_i^*}\right)^* x_i^* - g(x_1^*,x_2^*,\cdots,x_n^*) \left[ \left(\frac{\partial g}{\partial x_1^*}\right)^* \left(\frac{\partial g}{\partial x_2^*}\right)^* \cdots \left(\frac{\partial g}{\partial x_n^*}\right)^* \right]. \quad (3)$$

Step 7. $\beta$ can be calculated as

$$\beta = \sqrt{\sum_{i=1}^{n} (x_i^*)^2}, \quad (4)$$

indicating that its value is equal to the distance between $(x_1^*,x_2^*,\cdots,x_n^*)$ and the origin. The convergence tolerance for $\beta$ is assigned.
Step 8. Eq. (1) can be rewritten as

$$x_i^* = \mu_{x_i}^* + \sigma_{x_i}^* x_i^*,$$  \hspace{1cm} (5)

implying that $x_i^*(i=1,2,\cdots,n)$ are modified and $g(x_1^*,x_2^*,\cdots,x_n^*)$ can therefore be redetermined. The convergence tolerance for $g(x_1^*,x_2^*,\cdots,x_n^*)$ is assigned. Steps 3 to 8 are repeated until the convergence tolerances for both $\beta$ and $g(x_1^*,x_2^*,\cdots,x_n^*)$ are achieved.

Eqs. (1), (2) and (5) will also be valid for the normal variables in $X_i(i=1,2,\cdots,n)$ if $\mu_{x_i}^*$ and $\sigma_{x_i}^*$ are replaced by their mean values $\mu_{x_i}$ and standard deviations $\sigma_{x_i}$ ($i=1,2,\cdots,n$), respectively. $p_f$ can be approximately estimated based on the convergent $\beta$.

The finite difference method used herein is a perturbation-based approach. The computational procedure is summarized as follows (Haldar and Mahadevan, 2000b):

Step 1. The initial values of $X_i$, i.e., $X_i^0$ ($i=1,2,\cdots,n$), are assumed to be $\mu_{x_i}$ ($i=1,2,\cdots,n$), respectively.

The corresponding value of $Z$ before perturbation can therefore be determined as

$$Z_0 = g(X_1^0,X_2^0,\cdots,X_n^0).$$  \hspace{1cm} (6)

Step 2. The small and positive $\Delta X_i$ with respect to the perturbation of $X_i$ is given. $\Delta X_i$ is assumed to be proportional to $\sigma_{x_i}$. $X_i^0$ is replaced by $X_i^0 + \Delta X_i$ and $X_i^0$ ($i=2,3,\cdots,n$) remain the previous values. The corresponding value of $Z$ after perturbation can therefore be determined as

$$Z_1 = g(X_1^0 + \Delta X_1,X_2^0,\cdots,X_n^0).$$  \hspace{1cm} (7)

Step 3. The difference of $Z$ before and after perturbation can be calculated as

$$\Delta Z = Z_1 - Z_0.$$  \hspace{1cm} (8)

The derivative of $Z$ with respect to $X_i$ can be approximately estimated as

$$\frac{\Delta Z}{\Delta X_i}.$$  \hspace{1cm} (9)

Step 4. Similarly, the derivatives of $Z$ with respect to $X_i$ ($i=2,3,\cdots,n$) can also be approximately obtained as

$$\frac{\Delta Z}{\Delta X_i}$$  \hspace{1cm} (i=2,3,\cdots,n), respectively, by repeating Steps 2 and 3.
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By individually substituting \( g(X_1^n, X_2^n, \ldots, X_n^n) \) and \( \frac{\Delta Z}{\Delta X_i} (i = 1, 2, \ldots, n) \) of the finite difference method for \( g(x_1^*, x_2^*, \ldots, x_n^*) \) and \( \left( \frac{\partial g}{\partial X} \right)^* (i = 1, 2, \ldots, n) \) of the Rackwitz-Fiessler method, these two methods can be combined (Haldar and Mahadevan, 2000b).

6. Numerical Examples

To illustrate the computational procedure in Figure 1, two numerical examples, i.e., the torsionally uncoupled and coupled systems, are provided to conduct the reliability analysis of high-rise buildings under wind loads for a variety of attack angles. The results can be used to capture the dynamic effects due to the structural eccentricity.

Four types of parameters: the high-rise building model, wind load model, occupant comfort criteria and reliability analysis, are considered in this study. All parameters of the two numerical examples are the same except the eccentricity between the elastic and mass centers. For the parameters of the high-rise building model, a 40-story building \((N = 40)\) with a height of 160 m is used. The geometric configuration and dynamic properties of each floor are assumed to be identical, as shown in Table I. Table II summarizes the parameters of the wind load model, where \( C_p \) and \( C_L \) are a function of \( \phi \) (Peng, 2005). Table III lists the parameters of the occupant comfort criteria, where \( F \) is selected from the natural frequency of the first mode of each system. The parameters of the reliability analysis are illustrated in Table IV, where \( X_i \) and \( X_2 \) are employed to simulate \( E_{x_i} \) and \( E_{y_i} \), respectively. For both the torsionally uncoupled and coupled systems, \( \mu_{x_i} = E_{x_i} \) and \( \mu_{y_i} = E_{y_i} \) are given, and the probability distribution of \( X_1 \) and that of \( X_2 \) are assumed to be identical. Three types of probability distributions: the normal, lognormal and type I extreme value distributions, are used to model the uncertainties of both \( X_1 \) and \( X_2 \).

The acceleration at the top floor corner is the target of both the deterministic and reliability analyses. This is because such response is the maximum throughout the system. The relationships between the peak acceleration at corner of the 40th floor, i.e., the demand, and \( \phi \) for the torsionally uncoupled and coupled systems are shown in Figure 5(a) and 5(b), respectively. The allowable peak acceleration independent of \( \phi \), i.e., the capacity, is displayed in the figures. Both the figures illustrate that the demand is comparatively lower than the capacity for each \( \phi \). Consequently, the occupant comfort criteria are satisfied in the two numerical examples from the viewpoint of deterministic approaches. These two figures also show that the maximum peak acceleration occurs when the wind direction is parallel to the \( x \) axis, i.e., \( \phi = 0^\circ \) or \( 180^\circ \). The peak acceleration of the torsionally coupled system is relatively higher than that of the torsionally uncoupled system for each \( \phi \) due to the coupled mode effects.
Table I. Parameters of the high-rise building model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>(B_i)</td>
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<td>(H_i)</td>
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<td>[m]</td>
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<tr>
<td>(E_y)</td>
<td>[m]</td>
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</tr>
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<td>(A_y)</td>
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<td>(K_{y})</td>
<td>[N/m]</td>
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<td>(K_{\theta})</td>
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<tr>
<td>(A_1)</td>
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TUS: Torsionally uncoupled system  
TCS: Torsionally coupled system

Table II. Parameters of the wind load model.

<table>
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<td>(\rho)</td>
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<td>(C_o)</td>
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<tr>
<td>(C_i)</td>
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<td>(Peng, 2005)</td>
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Table III. Parameters of the occupant comfort criteria.

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<tr>
<td>(F)</td>
<td>[Hz]</td>
<td>0.5164 (TUS) - 0.5106 (TCS)</td>
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<td>(T)</td>
<td>[s]</td>
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<tr>
<td>(R)</td>
<td>[yr]</td>
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</tr>
</tbody>
</table>

TUS: Torsionally uncoupled system  
TCS: Torsionally coupled system
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Table IV. Parameters of the reliability analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
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<td>$\mu_{x_1}$</td>
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<tr>
<td>$\mu_{x_2}$</td>
<td>[m]</td>
<td>0 (TUS) − 2.4 (TCS)</td>
</tr>
<tr>
<td>$\sigma_{x_1}$</td>
<td>[m]</td>
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</tr>
<tr>
<td>$\sigma_{x_2}$</td>
<td>[m]</td>
<td>0.8</td>
</tr>
</tbody>
</table>

TUS: Torsionally uncoupled system  
TCS: Torsionally coupled system

Figure 5. Relationships between the peak acceleration at corner of the 40th floor and the attack angle.

The reliability analysis is conducted based on the demand and capacity obtained by the deterministic analysis. The relationships between the probability of dissatisfaction with occupant comfort criteria for three types of probability distributions of the structural eccentricity, i.e., the normal, lognormal and type I extreme value distributions, and $\phi$ for the torsionally uncoupled and coupled systems are shown in Figure 6(a) and 6(b), respectively. Both the figures illustrate that the probability for the case of the normal distribution is relatively higher than that for the other two cases for each $\phi$. Furthermore, the probability for the case of the lognormal distribution is close to that of the type I extreme value distribution for each $\phi$. The findings indicate that, compared to the lognormal and type I extreme value distributions, the normal distribution can be used to more conservatively simulate the uncertainties of the eccentricity between $EC_i$ and $MC_i$ in the two numerical examples from the viewpoint of probabilistic approaches. These two figures also show that the maximum probability occurs when the wind direction is parallel to the $x$ axis, i.e., $\phi = 0^\circ$ or $180^\circ$. The probability of the torsionally coupled system is relatively higher than that of the torsionally
uncoupled system for each $\phi$ due to the coupled mode effects. The results are in agreement with those obtained by the deterministic analysis.

![Diagram](image_url)

(a) Torsionally uncoupled system  
(b) Torsionally coupled system

*Figure 6. Relationships between the probability of dissatisfaction with occupant comfort criteria and the attack angle.*

7. Conclusions

The objective of this paper is to conduct the reliability analysis of high-rise buildings under wind loads. Two numerical examples, i.e., the torsionally uncoupled and coupled systems, are provided to capture the dynamic effects of structures with eccentricity between the elastic and mass centers. The framework of this research consists of two stages. The first stage includes two parts: the deterministic analysis of wind-induced acceleration for a variety of attack angles, i.e., the demand, and the determination of allowable acceleration based on the occupant comfort criteria for wind-excited buildings, i.e., the capacity. According to the results obtained in the first stage, the reliability analysis is conducted in the second stage, which can predict the probability of dissatisfaction with occupant comfort criteria for three types of probability distributions of the structural eccentricity, i.e., the normal, lognormal and type I extreme value distributions.

In the first stage, both the examples illustrate that the demand is comparatively lower than the capacity for each attack angle. Consequently, the occupant comfort criteria are satisfied in the two numerical examples from the viewpoint of deterministic approaches. These two examples also show that the maximum peak acceleration occurs when the wind direction is parallel to the $x$ axis. The peak acceleration of the torsionally coupled system is relatively higher than that of the torsionally uncoupled system for each attack angle due to the coupled mode effects.

In the second stage, both the examples illustrate that the probability for the case of the normal distribution is relatively higher than that for the other two cases for each attack angle. Furthermore, the
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probability for the case of the lognormal distribution is close to that of the type I extreme value distribution for each attack angle. The findings indicate that, compared to the lognormal and type I extreme value distributions, the normal distribution can be used to more conservatively simulate the uncertainties of the eccentricity between the elastic and mass centers in the two numerical examples from the viewpoint of probabilistic approaches. These two examples also show that the maximum probability occurs when the wind direction is parallel to the x axis. The probability of the torsionally coupled system is relatively higher than that of the torsionally uncoupled system for each attack angle due to the coupled mode effects. The results are in agreement with those obtained by the deterministic analysis.

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