ON THE DYNAMICS OF TIMBER STRUCTURES SUBJECTED TO WIND ACTIONS

GEORGESCU, Migdonia
National Museum of Romanian History,
12 Calea Victoriei, Bucharest 030026

MUNTEANU, Ligia
Institute of Solid Mechanics, Romanian Academy,
15 Ctin Mille , Bucharest 010141

Abstract

The paper analyses the wind-induced responses of multi-storey timber buildings. These structures are characterized by light weight and high flexibility in comparison with traditional materials. Therefore, the analysis of the wind induced vibrations are very important for their designing.

Keywords: *wind load on timber structures, wind effects on timber structures.*

ACM/AMS Classification: 74F10

1. **Introduction**

The loads such as wind, snow, earthquake and floor loads have become significant because of increasing number of high-rise structures. The wind is an important factor in design not only for light low-slope roofs, walls and structures with aerodynamic shapes, but also for urban multi-storey buildings having the main structural material the timber (Thomson 2009; Reid 2009; Unger, Hein and Göckel 2010). The tall buildings extended into regions of high wind velocity have caught the attention of researchers.

Wind usually refers to parallel motions of air to the earth's surface, and we can say that the wind-induced vibrations induced for laminar wind flow with velocity up to 7 m/s is a damaging mechanism for the structure itself. The method of aeolian vibration control is based on the energy balance principle that takes into account the wind energy input, the energy dissipated by the structure, which are used for mitigation the vibration level of structures subjected to wind actions. Both static and dynamic loads are capable of producing large tip deflections in structures (Drybre and Hansen 1997; Davenport 1967, 1999). The speed of the wind varies with height of the structures and the type of ground roughness.

This paper analyzes only the the structures having the maximum dimension, horizontal or vertical, less than 20m (class A - according to the code of practice for design loads (Eurocode 1 2005). The wind speed over the surfaces of the building is randomly distributed, in the sense that the wind speed varies in space and time, and so the time-history of forces on one part of the building surface is different from that experienced by another. These features make the modeling difficult. The correlation between forces on different parts of the structure affects the behaviour of the structure as a whole (Reynolds et al. 2011). Different methods for describing the wind vibrations of structures based on the representation of wind speed as a stationary random variable have been proposed (Davenport 1961; Simiu and Scanlan 1986; Solari 2002). A power spectral density function for velocity can be defined which is constant with time, such as that shown in Fig. 1 (after after Eurocode 1 (BS EN 1991-1-4, 2005).

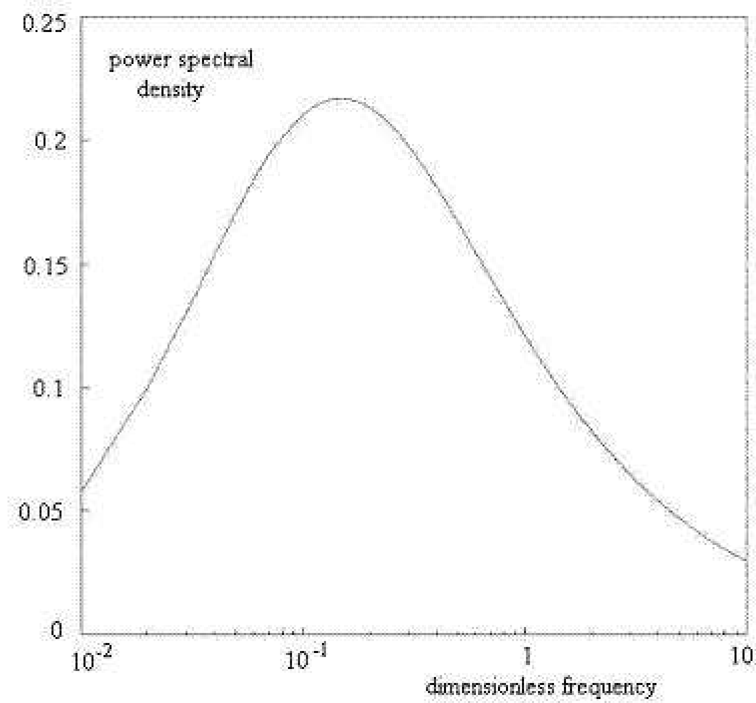

Fig.1. Dimensionless power spectra density function for wind velocity, after Eurocode 1 (BS EN 1991-1-4, 2005).

2. **Formulation of the problem**

Consider a 3-storey building, based on the timber materials and subjected to wind actions. Such a structure is able to resists to the conventional loads including the wind load, due to the fact that the timber has the ratio between stiffness and weight similar to that of steel, but about 7 or 8 times that of concrete. The timber-based structures are lighter than the structures made from steel or concrete, the density of timber being about 10% that of steel. In the same time, if the structure is slenderness and light, it can be susceptible to wind actions.

Let us start with the motion equations of a multi-storey timber building, written under the form

$$M\ddot{x} + C\dot{x} + Kx = RF(t) \tag{1}$$

where x, $\dot{x}$, and $\ddot{x}$ represent the displacement, velocity, and acceleration vectors, while M, C, K and R represent the mass, damping, stiffness and the force corresponding matrices, respectively. The system (1) can be rewritten as

$$\dot{x} = v, \; \dot{v} = -M^{-1}Cv - M^{-1}Kx + M^{-1}RF, \tag{2}$$

where x and $\dot{x}$ are the displacement and velocity vectors, respectively. Let us denote with $X = [x, v]$ the state vector. In this case, the state space representation is

$$\dot{X} = AX + B, \; A = \begin{pmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{pmatrix}, \; B = \begin{pmatrix} 0 \\ M^{-1}RF \end{pmatrix} \tag{3}$$

By denoting the first natural circular frequency of the structure by ω_1, and the average value of the first twenty natural circular frequency by ω_2, we calculate the damping matrix by using the Rayleigh damping expression (Zhou et al. 2011)

$$C = \alpha M + \beta K \tag{4}$$

where, α and β have the following form

$$\alpha = \frac{2\omega_1\omega_2\left(\varsigma_1\omega_2 - \varsigma_2\omega_1\right)}{\omega_2^2 - \omega_1^2}, \; \beta = \frac{2\left(\varsigma_2\omega_2 - \varsigma_1\omega_1\right)}{\omega_2^2 - \omega_1^2} \tag{5}$$

The root mean square (RMS) value of the wind-induced displacement response of the structure is (Zhou et al. 2011)

$$\sigma_R = \sqrt{E\left[x(t) - \overline{R}\right]^2} \tag{6}$$

where $\overline{R}$ is the main response. The gust response factor G, which reflects the dynamic amplification when the structure is subjected to fluctuating wind loads (Zhou and Kareem 2001), is computed as

$$G = \frac{\widehat{R}_p}{R} \tag{7}$$

where $\widehat{R}_p$ is the peak response, defined by

$$\widehat{R}_p = \overline{R} \pm g\sigma_R \tag{8}$$

In (8), g is the peak factor which is evaluated from the wind tunnel experiments, and generally ranges from 2.5 to 4 (Zhou et al. 2011). Every structure has a natural frequency of vibration, and if the dynamic loading occur at or near it, the structural damage becomes important.

3. Results

The system under study is a three-story system. The basic wind speed is 30m/s. The value of is taken as 2.5 (the probability of exceedind a value above RMS less than 0.62%). For a single degree of freedom system with stiffness k, the decrement of damping δ is given by

$$\delta = \frac{W_d}{kx\Omega} \tag{9}$$

where W_d is the dissipated energy in the cycle of displacement from $+x$ to $-x$, and $\Omega = \frac{\omega}{\omega_n}$ is the ratio of the excitation frequency to the natural frequency of the system. For uncoupled motion equations (1), the total damping is calculated as a sum of the energy dissipation for each degree of freedom. The relevant parameters of the system are

$$M = \begin{bmatrix} 11136 & 0 & 0 \\ 0 & 1144 & 1144 \\ 0 & 0 & 1144 \end{bmatrix}, \; K = \begin{bmatrix} 374882 & -464839 & 119690 \\ -464909 & 893225 & -556307 \\ 116911 & -556345 & 937363 \end{bmatrix},$$

$$C = \begin{bmatrix} 216 & -11 & 9 \\ -11 & 241 & -21 \\ 9 & -21 & 237 \end{bmatrix}$$

Figs. 2, 3 and 4 show the time history of displacements, in the resonant regime. The building has the first natural frequency less than 1 Hz (natural period greater than 1s), therefore the wind induced vibrations are significant. The peak responses x_3, x_2 and x_1 are 5.144, 3.225 and 1.227 [cm], respectively. The variation of the damping ratio with respect to the amplitude of the motion, calculated according to (9) is displayed in Fig.5.

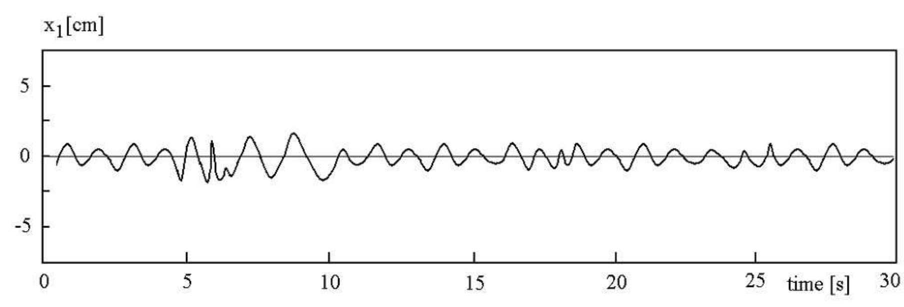

Fig. 2, Time history of displacement .

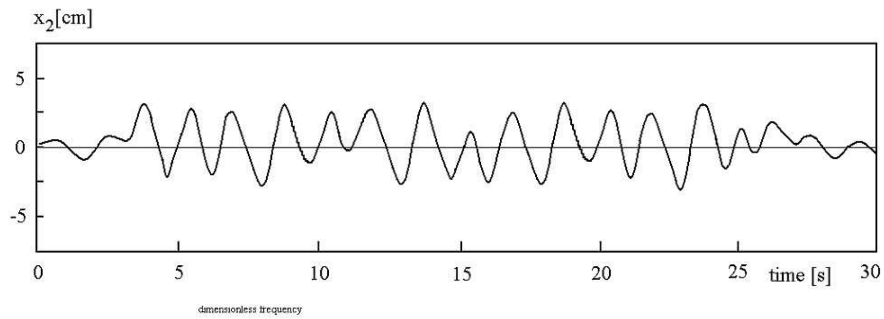

Fig. 3. Time history of displacement .

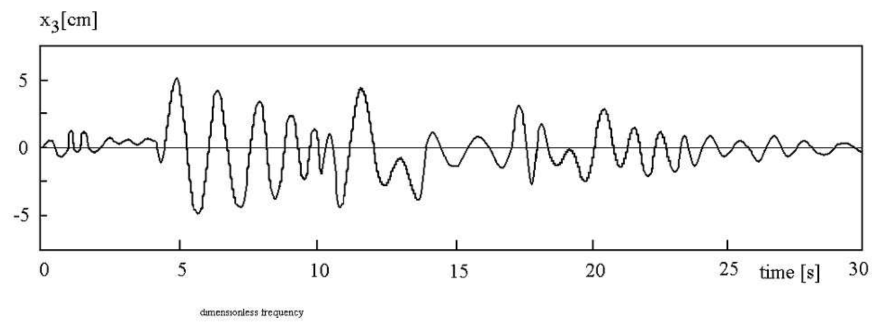

Fig. 4. Time history of displacement .

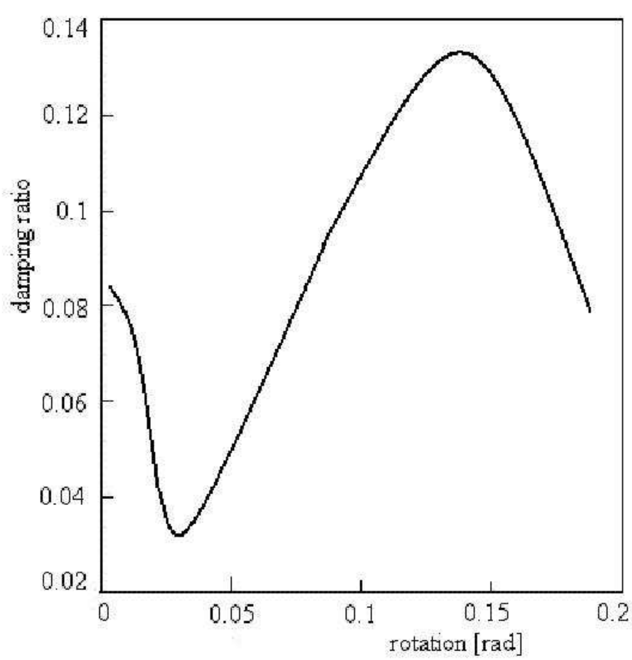

Fig.5. Variation of the damping ratio with respect to the rotation amplitude.

4. **Conclusions**

High structures characterized by a relevant slenderness, low weight and a small damping ratio can be susceptible to wind actions. The paper analyses the wind-induced responses of 3-storey timber building. This structure has a high flexibility in comparison with traditional materials, and therefore the dynamic response is significant. Its resonant response depends on the wind loading and its first natural frequency. The wind energy is smaller at frequencies about 1 Hz, therefore the resonant response of the building with the first natural frequency above 1 Hz, will be sufficiently small. When the building has a height exceeding 4 times the least horizontal dimension or when the natural frequency is less than 1Hz, the wind induced vibrations should be investigated.

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