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Relationship between specified ductility and strength demand reduction for single degree-of-freedom systems under extreme wind events

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ABSTRACT

Structural failures could be attributed to extreme wind events, such as hurricanes, tornadoes and wind bursts. These events with very low probability of occurrence should be properly included in the structural design. Large magnitude forces, greatly exceeding the ordinary wind storm loads, mean that considering extreme wind loading will result in increased cost for the structural design. An alternative design approach consists in dissipating the energy coming from the extreme wind event through the hysteretic behaviour, in a similar measure as what is used in earthquake engineering. This paper aims at establishing the relationship between the desired ductility of the structures and the reduction in structural strength required to withstand extreme wind events in order to reduce the cost of structures. Digitally generated wind as well as in situ measurements of winter storm and hurricane wind are used in this study. The study focused on single-degree-of-freedom (SDOF) systems to represent a wide range of structural behaviour. A simplified linearized method to estimate nonlinear response is proposed here. The applicability of the present study on real wind records is verified.

1. Introduction

Major damages during recent hurricanes, tornadoes and wind bursts have highlighted the necessity to properly include the effect of wind loadings from these events in the structural design (e.g. Johnson, 2008). Nonetheless, this approach will result in increased cost of structure when traditional linear elastic wind design method is used. In the case of low probability of occurrence events, namely extreme events, modern structural design relies on ductile modes of failure and redundant structural paths with recent advances in progressive collapse approach. Hence, it is useful to evaluate how this approach could influence the design under extreme wind or very low probability of occurrence wind storm. In addition, it is of interest to design ductile system instead of elastic system in order to reduce loads carried to the foundation, to reduce the cost of design for these low probabilities of occurrence wind events.

Several previous studies have been dedicated to the nonlinear behaviour of structures under extreme wind loading (Vickery, 1970; Chen and Davenport, 2000; Hong, 2004). The study by Vickery (1970) proposed a simplified analytical elastic approach to predict the nonlinear response due to wind loading of lightly damped SDOF systems with low natural frequencies. In that study, the wind loading was obtained from one sample record of the previous wind tunnel study, which was equivalent to 1 h wind. It was concluded that for the type of structure studied, to produce severe damage, it would be able to handle 20% stronger wind than what was required to produce yielding of the structure.

Chen and Davenport (2000) studied the vulnerability of tall buildings under hurricanes. The study was focused on a typical building data and was conducted using a very large number of simulated storms. For the hurricane wind, since the mean wind speed varies in time, the analysis was divided by blocks and was computed using the approach proposed by Vickery (1970). Ductility demand from the typical building studied was evaluated. It was concluded that ductile structure had a better reserve of safety than brittle structure with the same static strength.

In Hong (2004), nonlinear SDOF systems were analysed numerically. The study was aimed at validating previous method based on linearized analysis by Vickery (1970) for bilinear inelastic SDOF systems. The study concluded that the approach by Vickery would provide conservative estimate for low frequency systems, while for higher range frequency the estimate becomes highly inaccurate and it could provide unconservative estimate for the covariance of the response. In his study, ductility demand was also evaluated for a number of frequencies. In addition, it was found that the ductility demand due to the wind action over a period of 1 h for flexible structures could be much less than that for rigid structures and that strain-hardening

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reduces significantly than the ductility demand. It also mentioned that the scatter associated with the ductility demand could be relatively large.

It can be concluded from the previous studies that a structure could be designed for a reduced wind load if it has sufficient ductility. However, previous studies did not provide a comprehensive overview of the relationship between the ductility and reduction of strength for a wide range of natural frequencies to eventually evaluate the interest of using ductile design for structures under extreme wind load. In addition, the application of in situ measurements of extreme wind events has never been done before.

The objective of this paper is to evaluate how ductile behaviour can be taken into account in the design of SDOF systems under extreme wind. To reach this goal, the following steps are taken: (i) to establish general relationship between ductility and reduction of strength demand under wind load as well as to evaluate the influence of wind and structural variables using digitally generated wind data, this is explained in Section 2; (ii) to estimate linearization method for the use in spectral stochastic approach based on the results from (i), as detailed in Section 3; (iii) by using real winter storm and hurricane wind to evaluate the validity of (i) and (ii), as described in Section 4.

2. Parametric study using digitally generated wind

Ideally, only wind speed recorded during extreme events such as wind storms and hurricanes should be used to evaluate the influence of wind loading on nonlinear systems. These extreme wind records are available, but they do not span all possible characteristics of wind that can be found in reality. For this reason, in this study, it was decided to use digitally generated wind records to sweep through a number of wind data sets so that they represent different types of terrains to evaluate the effect of certain characteristics on the relationship between ductility and design strength.

It is understood that those generated winds used here are representative of actual wind storm in terms of the spectral characteristics because they are generated from specified target spectra using spectral stochastic approach (Shinozuka and Deodatis, 1991), but may yield different results for nonlinear systems as compared to the real wind, especially non-stationary wind such as hurricane. Therefore, available real wind data are used in Section 4 of this paper to check the results of the parametric study described here, in this section. To evaluate more thoroughly the general structural behaviour for varying wind loading characteristics, wind speed data were digitally generated using the software WindGen (Hang et al., 2005).

The main purpose of the parametric study in this section is to evaluate the influence of: (i) turbulence intensity of wind, I_u (the characteristics of the generated wind are detailed in Section 2.2); (ii) natural frequency, f_1, of SDOF system; and (iii) bilinear constitutive law with strain hardening defined by the strain hardening slope αk. A short discussion on the influence of aerodynamic damping, ξ_a, is also presented. Table 1 summarizes the SDOF system variables used in this study. In addition to the previously introduced parameters, in this table, β is the strength factor that will be used to obtain the desired specified ductility, μ.

2.1. Description of the SDOF systems and the response calculation method

A simple SDOF system under wind loading is studied here, as shown in Fig. 1. The wind force on structures depends on the total wind speed $U(t)$, which is random in nature, varies with height z and time t. The wind speed $U(t)$ is divided into two components, namely the mean wind component $\overline{U}$ and the turbulent wind component $u(t)$, and it is expressed as

Table 1
SDOF system variables for the parametric study.

Variables	Description and range
Constitutive law	(a) Perfect elastoplastic $\alpha=0$ (b) Bilinear with strain hardening $\alpha=0.05$
Natural frequency	$0.1\leq f_1\leq 5.0$ Hz with $\Delta_{f_1}=0.05$ Hz for $f_1\leq 1$ Hz $\Delta_{f_1}=0.50$ Hz for $1<f_1\leq 3$ Hz $\Delta_{f_1}=1.00$ Hz for $3<f_1\leq 5$ Hz
Strength factor	To obtain the desired specified μ $0.40\leq\beta\leq 0.95$ with $\Delta\beta=0.05$

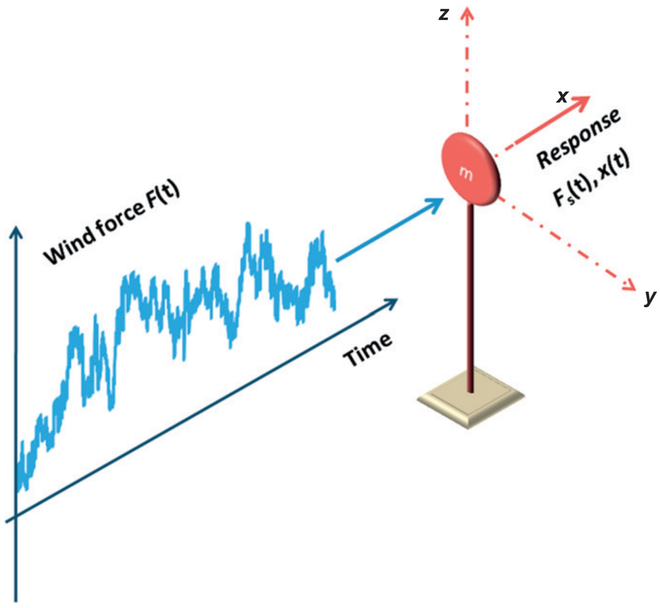

Fig. 1. SDOF system used in this study.

$$U(t)=\overline{U}+u(t) \tag{1}$$

The turbulent wind component $u(t)$ is defined by its power spectral density (PSD) and depends on the terrain and the wind type. In time domain, the total drag force $\overline{F}(t)$ induced by the wind is given by (Simiu and Scanlan, 1996)

$$\overline{F}(t)=\tfrac{1}{2}\rho_a C_d A[\overline{U}+u(t)]^2 \tag{2}$$

where ρ_a is the air density; C_d is the drag coefficient; A is the exposed area to the wind loading; $\overline{U}$ is the mean wind speed; and $u(t)$ is the turbulent wind speed. For the present study, the wind speed U, $\overline{U}$ and $u(t)$ are the wind components perpendicular to the surface of the SDOF system (see Fig. 1). In this study, $z=10$ m, $C_d=1$ and $A=10$ m^2. The total force defined in Eq. (2) does not include the part of the force that comes from the velocity of the structure. This force component is taken into account by the inclusion of the velocity and the aerodynamic damping term in the equation of motion to be solved. This is because the actual aerodynamic damping is related to too many parameters for the actual value to be added in the analysis. When the system is subjected to the wind force $\overline{F}(t)$, the response of the system can be obtained by solving the equation of motion:

$$m\ddot{x}+c\dot{x}+F_s(x,\dot{x})=\overline{F}(t) \tag{3}$$