Structural Safety 58 (2016) 1–10

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Fragility analysis and estimation of collapse status for transmission tower subjected to wind and rain loads

Xing Fu *, Hong-Nan Li, Gang Li

Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116023, China
State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116023, China

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form 15 August 2015
Accepted 21 August 2015
Available online 9 September 2015

Keywords:
Transmission tower
Wind and rain loads
Equivalent basic wind speed
Fragility analysis
Nonlinear analysis
Critical collapse curve

ABSTRACT

In this paper, the fragility analysis and concept of critical collapse curve for transmission tower subjected to wind and rain loads are presented to acquire the collapse equivalent basic wind speed and most unfavorable combinations of wind and rain loads corresponding to collapse status. The calculating method for wind and rain loads is simplified and the error analysis is performed to validate its effectiveness. The concept of equivalent basic wind speed is used to conduct the fragility analysis of transmission tower subjected to wind and rain loads which avoid the complex formula of rain load and the choice of different combinations of basic wind speed and rain intensity, and then the concept of critical collapse curve is proposed to evaluate the collapse status of transmission tower. At last the influence of wind attack angle and wind spectrum on the fragility and critical collapse curves is discussed, and results show that the wind attack angle and wind spectrum have a great influence on fragility and critical collapse curves. In this study, it can be seen that the use of equivalent basic wind speed make it possible to conduct the fragility analysis under wind and rain loads and the proposed concept of critical collapse curve is very convenient to evaluate the collapse status for structures subjected to wind and rain loads. In addition, the rain load has a great contribution to the tower collapse and should be paid more attention during severe gales and thunderstorms.

1. Introduction

Transmission tower is a supporter of power consumer, and its collapse often causes great economic loss and many accidents. In recent years, the fact of many transmission tower-line systems collapsed during typhoons or hurricanes attracts most researchers' attention. Typhoons or hurricanes are always accompanied by the strong rainfall, and the influence of rain load on the tower collapse has not been studied before. Therefore, considering the rain load, even the action of both wind and rain loads together is very necessary and significant.

Wind-driven rain (WDR) is the rain that has a horizontal velocity component. Choi [1–3] made major breakthroughs in the numerical simulation of WDR by using computational fluid dynamic. Blocken and Carmeliet [4–6] have extended the Choi's simulation technique by adding a temporal component and developing a new weighted data averaging technique, allowing for the determination of both the spatial and temporal distribution of WDR. Li et al. [7] proposed a new computational approach for the rain load on the transmission tower, and carried out the dynamic response analyses and experiments of the transmission tower under the wind and rain excitations. The results showed that the proposed approach agrees well with the wind tunnel test and the rain load influence on the transmission tower should not be ignored during the strong rainstorm. Fu et al. [8] modified the existed rain load model [7] by introducing velocity ratio of raindrop horizontal velocity to corresponding wind speed.

Ibarra [9] proposed a methodology for evaluating the global incremental (sidesway) collapse based on a relative intensity measure instead of an Engineering Demand Parameter. The proposed method was applied to the development of collapse fragility curves. Nielson and DesRoches [10] gave an expanded methodology for the generation of analytical fragility curves for highway bridges, where the contribution of major components of the bridge, such as columns, bearings and abutments, to its overall bridge system fragility, was considered, which showed that the bridge as a system is more fragile than any one of individual components. Padgett and DesRoches [11] presented an analytical methodology for developing fragility curves to classify retrofitted bridge systems and results indicated the importance of evaluating the impact of retrofit not only on the targeted response quantity and component

* Corresponding author at: Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116023, China.

http://dx.doi.org/10.1016/j.strusafe.2015.08.002
0167-4730/

vulnerability but also on the overall bridge fragility. Rota et al. [12] put forward a new analytical approach for the derivation of fragility curves for masonry buildings based on the nonlinear stochastic analysis of building prototypes. Billah and his colleagues [13] used fragility curves to assess the relative performance of various retrofit multicolumn bridge bents under both near-fault and far-field seismic ground motions.

Until now, the seismic fragility analysis has been studied for a long time and its importance has been shown with significance. However, the fragility analysis under wind load is just in an initial stage. Lee and Rosowsky [14] investigated a fragility assessment for roof sheathing in light frame constructions built in strong wind regions and the presented fragility models that can be used to develop performance-based design guidelines for wood frame structures as well as tools for condition assessment and loss estimation for use with the existing building inventory. Lee and Rosowsky [15] described a procedure to develop fragility curves for wood frame structures subjected to lateral wind loads, and a quick analysis to develop approximate fragilities is conducted. For the simulation of the along-wind dynamic response of tall buildings under turbulent winds, Smith and Caracoglia [16] presented a numerical algorithm and then the fragility curves were derived to estimate the performance based on the proposed numerical algorithm. Herbin and Barbato [17] developed a methodology for the windborne debris impact fragility curves for building envelope components during hurricanes. Seo and Caracoglia [18] used fragility analysis to estimate life-cycle monetary loss of long-span bridges due to wind hazards. Shafieezadeh and his colleagues [19] established a probabilistic framework for the age-dependent fragility analysis of wood utility poles against hurricanes and strong winds.

Although the rain load formula has been proposed and validated, there are limited investigations on the rain load influence on transmission tower. The fragility analysis has been widely used in seismic engineering field [9–13,20–26]. Whereas, it can be seen from above reviews that research achievements of fragility analysis subjected to wind load are very limited, and the production of this approach for the transmission tower subjected to wind and rain loads is even fewer and has not been found to be published in literature so far. Given all this, a method of fragility analysis subjected to wind and rain loads using equivalent basic wind speed is proposed in this paper, and then the concept of critical collapse curve is also presented to obtain the most unfavorable combinations of basic wind speed and rain intensity corresponding to collapse status.

2. Theoretical method for calculating wind and rain loads

The mean wind speed varying with altitude can be obtained by the exponential wind profile expression:

$$V_a = V_{10}\left(\frac{H}{10}\right)^{\alpha} \tag{1}$$

where V_{10} is the basic wind speed representing the mean wind speed during 10 min at the altitude of 10 m, H is the altitude, and α is the ground roughness coefficient.

The wind pressure in free wind field and wind load acting on structures are written by:

$$P_w = \frac{1}{2}\rho_a V_a^2 \tag{2}$$

and

$$F_w = \mu_s\left(\frac{1}{2}\rho_a V_a^2\right)A \tag{3}$$

where ρ_a is the air density taking 1.235 kg/m^3, μ_s is the body shape parameter, and A is the projected area of structure in the windward direction.

The rain pressure for the specified rain diameter yields [7,8]:

$$P_r(V_a, R, D, H, \alpha) = k\rho_w S(\gamma(H, D, \alpha)V_a, R)n(D, R)\gamma^3(H, D, \alpha)V_a^3 D^3 \tag{4}$$

where k is a factor taking 102.0 in $1/m$, ρ_w is the raindrop density taking 1000 kg/m^3, D is the raindrop diameter, $n(D, R)$ is the raindrop spectrum which means the raindrop size distribution, γ is the velocity ratio, and $S(V_r, R)$ denotes the area of the normalized curve in Fig. 1 integrating from 0 to the time of Δt.

Based on the Marshall–Palmer raindrop spectrum [27], the raindrop size distribution is expressed as:

$$n(D, R) = n_0 \exp(-\Lambda D) \tag{5}$$

where $n_0 = 8 \times 10^3$ in $1/(\text{m}^3\ \text{mm})$, $\Lambda = 4.1R^{-0.21}$ in 1/mm, and R is the rain intensity (mm/h).

Δt can be calculated by:

$$\Delta t = \frac{\sqrt{2}}{\sqrt[3]{N(R)}V_r} \tag{6}$$

where V_r is the raindrop horizontal velocity and $N(R)$ is the total number of raindrops per unit volume taking $\int_0^\infty n(D, R)dD$.

The velocity ratio is defined as the ratio of raindrop horizontal velocity to the corresponding wind speed, which can be expressed as [8]:

$$\gamma(H,D,\alpha) = \frac{V_r}{V_a} = \begin{cases} (0.2373H^{-0.5008} - 0.0167)\left(\frac{D}{3}\right)^{0.8}\left(\frac{\alpha}{0.12}\right) + 1 & (H \leqslant 150\,\text{m}) \\ 1 & (H > 150\,\text{m}) \end{cases} \tag{7}$$

The rain load for a specified rain intensity and wind speed can be derived from integrating Eq. (4) as:

$$F_r = \int_0^\infty P_r(V_a, R, D, H, \alpha)AdD \tag{8}$$

Wind load is very easy to calculate based on Eq. (3), and yet the form of Eqs. (4) and (8) is so complex that it can only be obtained by programming. Thus, it will be very meaningful to propose a simplified method to calculate wind and rain loads for its easy and wide applications.

3. Simplified method for calculating wind and rain loads

3.1. Simplified method

For simplifying the calculating process of wind and rain loads, the equivalent basic wind speed (EBWS) and equivalent ground roughness coefficient (EGRC) are employed, and the process of finding EBWS and EGRC is listed as below:

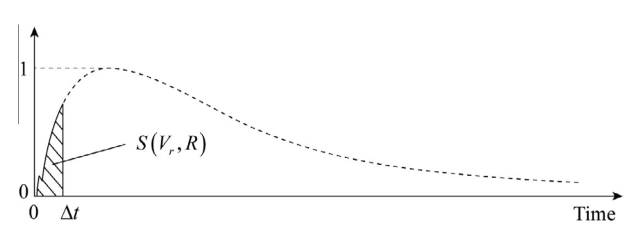

Fig. 1. Schematic of normalized curve and $S(V_r, R)$.