Engineering Structures 143 (2017) 549–557

Contents lists available at ScienceDirect

Engineering Structures

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

Performance-based design of steel towers subject to wind action

Rodolfo K. Tessari *, Henrique M. Kroetz, André T. Beck

Department of Structural Engineering, University of São Paulo, Av. Trabalhador São-carlense 400, 13566-590 São Carlos, SP, Brazil

ARTICLE INFO

Article history:
Received 21 September 2016
Revised 23 March 2017
Accepted 26 March 2017
Available online 29 April 2017

Keywords:
Performance-based Engineering
Performance-based Wind Engineering
Structural reliability
Probabilistic analysis
Latticed telecommunication tower

ABSTRACT

Performance-based Wind Engineering (PBWE) is a novel design philosophy that aims to identify and quantify the uncertainties involved in structural design, in order to ensure predictable performance levels to engineering structures. Due to the recent proposal of the methodology and formulation complexity, there are few studies related to PBWE, each presenting different limitations. This paper proposes an application of the Performance-based Wind Engineering methodology to the probabilistic analysis of steel towers, evaluating different calculation models for the estimation of wind forces on this type of structure. Uncertainties involved in the characterization of the wind field and the structural strength were investigated, and two procedures of the Brazilian winds standard NBR6123:88 for the estimation of wind forces on steel towers were analyzed. A case study concerning the reliability estimation of a telecommunication tower was also conducted. It was found that both studied calculation models lead to similar safety levels, and that the design of towers considering that wind always blows from the worst direction is too conservative. It is also shown that, in PBWE, minimum cost design can be guided by assigning same target reliability, but different mean recurrence intervals for different performance levels.

1. Introduction

Inherently random and knowledge-based uncertainties are part of the structural design process. Aleatory uncertainty is often associated to environmental hazards (e.g. earthquakes, storms, landslides and tornadoes), whose intensities and frequencies are difficult to predict, while epistemic uncertainty encompasses limited databases and limited models that cannot assure perfect representation of structural responses. Uncertainties can be reduced through research, but cannot be eliminated, giving rise to structural risks.

Risk represents a function of the likelihood of a hazardous event taking place, and its social and economic consequences. It strongly depends on location and typology of the concerned facility, since any structure is subjected to a certain range of hazards. Therefore, selection of the relevant threats to each structure and acknowledgment of the uncertainties involved is important and demands attention. To neglect or to underestimate risks may compromise structural safety, and may expose people to avoidable, dangerous situations; whereas overestimating risks can lead to misallocation of resources [1].

Classically, risk management in structural design problems is addressed through deterministic or semi-probabilistic approaches (encoded in design standards). In the deterministic scenario, load and resistance parameters are admitted as perfectly known and invariant. In the latter, factors of safety calibrated according to traditional engineering practice are applied to the nominal or characteristic values of design variables. Despite the advances in the field of structural engineering during the past decades, both approaches still present some flaws [2–5].

The search for more effective methods for quantifying and mitigating risks led to development of the Performance-based Engineering (PBE) approach. The definition of PBE was first outlined in SEAOC's Vision 2000 report [6] and soon became widespread in the literature [7–9]. The PBE design philosophy represents a paradigm in which the prescriptive approach imposed by structural standards is replaced by the quantitative assessment of design alternatives against performance objectives, described in probabilistic terms [10].

The first publications regarding performance-based procedures were developed in the United States for seismic design and retrofit of buildings [6,11]. These implementations were driven by the 1994 Northridge and 1995 Kobe earthquakes, that together caused a total estimated loss of U$120 billion [12], even though affected structures complied with seismic codes, based on traditional design philosophies, prevailing at the time [9].

* Corresponding author.
E-mail addresses: tessari.rodolfo@usp.br (R.K. Tessari), henrique.kroetz@usp.br (H.M. Kroetz), atbeck@sc.usp.br (A.T. Beck).

http://dx.doi.org/10.1016/j.engstruct.2017.03.053
0141-0296/

Naturally, the first-generation PBE procedures presented some shortcomings [13]. In order to fill these gaps, a more robust methodology was developed in the Pacific Earthquake Engineering Research (PEER) Center, that turned out to be the most popular and currently applied Performance-based Earthquake Engineering (PBEE) formulation [14].

PEER's PBEE methodology was built over the foundations of structural reliability theory. This provided a theoretical framework to the probabilistic treatment of uncertainties and an explicit system-level performance assessment [9]. Its successful applications made the technical and scientific community consider PEER's rational approach ideal for the design of structures subjected to natural hazards. In recent years, many studies have been carried out on the performance assessment of structures subject to tsunamis [15] and hurricanes [2,16,17].

Another branch of great interest for further developments deals with the application of PBE concepts to wind engineering. Performance-based Wind Engineering (PBWE) was first proposed in 2004 [18] as the result of the Italian PERBACCO project, and assumed a concise and general format in 2009, when its methodology was established [19].

Recently, studies illustrating the applicability of PBWE methodology and proposing incremental improvements have been published: Ciampoli, Petrini and Augusti [20] evaluated the performance of a long span suspension bridge; Ciampoli and Petrini [21] analyzed the structural behavior of a 74 floor building; and Petrini, Gkoumas and Bontempi [22] performed an extensive literature review on damage and loss analysis in order to expand the PBWE procedure. Griffis et al. [23] also briefly proposed an alternative procedure for PBWE, focusing on nonlinear dynamic analysis of structures.

The rapid evolution and diffusion of the PBWE concept, over the last years, is remarkable. However, due to the novelty and complexity of the methodology, there are still few studies related to the theme, each presenting different limitations. No studies addressing PBWE design of steel towers were found in the published literature. In this paper, the PBWE framework is adapted to analyze the structural behavior of such structures in probabilistic terms. Special attention is given to the choice of proper parameters characterizing the wind field and structural behavior, as well as to the comparison of different wind action models for steel towers. The developed methodology is demonstrated in application to a popular telecommunications steel tower.

2. The PBWE methodology

The present study is based on the Performance-based Wind Engineering framework proposed in [19,24]. The central objective of the PBWE procedure is to assess if a structural facility fulfills specific performance requirements (usually related to safety, functionality and comfort), as specified by end-users, stakeholders or society. It consists of the following steps [25]:

i. characterizing the wind hazard at the candidate location of the structure;
ii. probabilistic modeling of the wind-structure interaction phenomena;
iii. analyzing the structural response within the scope of stochastic mechanics;
iv. characterizing and evaluating the variables that express the structural damage and govern the considered performance measures;
v. defining the decision variables (*DV*s) that are appropriate to quantify the intended structural performances (mainly in terms of consequences of damage);
vi. assessing the structural risk based on the probabilistic description of the *DV*s;
vii optimizing design (i.e. minimizing risk or maximizing a utility function) by appropriate decision strategies.

The first step consists in choosing a set of intensity measure parameters (*IM*s) that are sufficient to describe the site-specific hazard (e.g. mean wind velocity, turbulence intensity, direction). Attention must be paid to the selection of each *IM*, since they have direct impact on the output of all the subsequent stages.

Step ii. corresponds to the choice and probabilistic characterization of a set of interaction parameters (*IP*s) able to represent the interaction between the environment and the structure. Aerodynamic coefficients and aeroelastic derivatives are proper examples of *IP*s.

The process continues (step iii.) with selection of the most significant random structural parameters (*SP*s) and engineering demand parameters (*EDP*s) that influence the structural behavior. Material and geometrical properties are normally chosen as *SP*s, whereas *EDP*s are represented by the acceleration, stress or displacement at selected points. Such parameters are then probabilistically assessed through structural response analyses.

In step iv., damage measures (*DM*s) and decision variables are specified in order to quantify the structural damage and the building performance, respectively. Both are strongly interconnected and depend on the considered facility type and usage. Typical *DM*s are the loss of occupant comfort and the damage to structural and non-structural components in a building, due to excessive vibration or displacements. *DV*s include the number of casualties, the economic losses or some threshold that represents the collapse or loss of serviceability condition during windstorms.

*DV*s which quantify the performance objectives must distinguish between low- and high-performance levels [1]: the former are related to *ultimate limit states* (ULS) and imply possible consequences on structural integrity and personal safety; the latter are associated to *serviceability limit states* (SLS) and affect operability and comfort.

Regardless of the target performance, in the original PBWE procedure (as in the PEER's approach), the structural risk is defined as the probability of a relevant *DV* exceeding a threshold value $\mathbf{dv}^*$:

$$\begin{aligned} G(\mathbf{dv}^*) &= P(DV > \mathbf{dv}^*) \\ &= \int\int\int\int\int G(\mathbf{dv}^*|DM) \cdot f(DM|EDP) \cdot f(EDP|IM, SP, IP) \\ &\quad \cdot f(IP|IM, SP) \cdot f(IM) \cdot f(SP) \cdot dDM \cdot dEDP \cdot dIP \cdot dIM \cdot dSP \end{aligned} \quad (1)$$

where $f(\cdot)$ symbolizes the probability density function, $f(\cdot|\cdot)$ the conditional probability density function, and $G(\cdot)$ the complementary cumulative distribution function.

Through the multiple integral expressed in Eq. (1), it is possible to separate the risk assessment into the previously stated elementary steps:

- site-specific hazard analysis and structural characterization, i.e. the assessment of $f(IM)$ and $f(SP)$, respectively;
- interaction analysis, that corresponds to the estimation of $f(IP|IM, SP)$;
- structural analysis, aimed at assessing the probability density function of the structural response $f(EDP|IM, IP, SP)$, conditional on the output of the previous steps;
- damage analysis, that gives the damage probability density function $f(DM|EDP)$ conditional on *EDP*;
- finally, loss analysis, that matches the value of $G(\mathbf{dv}^*|DM)$.

With respect to the PEER approach, the major advance provided by the PBWE methodology is the decoupled analysis of parameters that characterize the structural behavior from parameters that