Engineering Structures 78 (2014) 133–144

Contents lists available at ScienceDirect

Engineering Structures

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

Performance-based design and optimization of uncertain wind-excited dynamic building systems

Seymour M.J. Spence [*], Ahsan Kareem

NatHaz Modeling Laboratory, Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, United States

ARTICLE INFO

Article history:
Available online 15 August 2014

Keywords:
Performance-based design
Reliability-based design optimization
Reliability analysis
Aerodynamic loads
Monte Carlo simulation
Structural optimization
Wind engineering
Spectral proper orthogonal decomposition

ABSTRACT

Performance-based design is fast becoming the benchmark approach for achieving designs that rationally meet society's need for a truly safe built environment. While the principles of performance-based design have been vigorously adopted in the field of seismic engineering, the same cannot be said for wind engineering. There therefore exists the need to define appropriate frameworks that allow the principles of performance-based design to be fully embraced during the design of building systems to resist severe wind events. Obviously the ultimate goal of any project is not to simply meet the performance objectives, but to do so in an economically optimum fashion. This can only truly be achieved through the development of appropriate optimization strategies that rigorously embrace the inevitably uncertain and aleatory nature of both system and environment. This paper focuses on the development of a framework for the probabilistic performance-based assessment of large scale uncertain linear systems driven by experimentally estimated stochastic wind loads. In particular, a simulation-based method is proposed that centers on the concept of decoupling the inherently nested reliability/probabilistic analysis from the optimization loop through the definition of a series of high quality approximate subproblems. The way in which the decoupling is achieved allows practical problems characterized by hundreds of component-wise reliability constraints and high-dimensional discrete design variable vectors to be efficiently and rigorously solved. Examples are presented illustrating the practicality of the proposed approach.

1. Introduction

Performance-based design (PBD) is rapidly becoming the benchmark approach for designing civil structures and infrastructures to rationally resist both natural and man-made hazards. In the design of building systems against natural hazards, the principles of PBD have been widely adopted as a means for achieving earthquake resilient designs. Indeed, many of the prescriptions contained in international building codes and standards governing seismic design can be easily traced back to the principles of PBD (e.g. Eurocode 8 [1] and the ASCE 7-10 [2]). As an approach, PBD centers on the definition of a set of performance objectives (also known as goals or expectations) that must be satisfied by the building system under investigation. These objectives are in general set on request of the building's stakeholders or, more generally, on societal needs. Obviously, in order to asses whether a building system meets a set of chosen objectives, these last must be explicitly described in terms of appropriate models that are themselves defined in terms of suitable hazard, damage and response estimation models. Even though the principles of PBD are independent of whether these models are probabilistic or deterministic, the inherently aleatory and uncertain nature of the environment in which building systems are constructed, as well as the inevitable epistemic and knowledge uncertainties involved in describing such an environment, implies the necessity of using reliability/probabilistic models during the implementation of PBD. This need, among others, has spawned a new generation of rigorously probabilistic PBD procedures [3–7]. While there has been abundant research concerning the development of appropriate probabilistic models for implementing PBD in the field of seismic engineering [3–8], the explicit implementation of PBD in the area of wind engineering has not seen the same thrust. This is most likely due to the fact that wind engineering is traditionally based on probabilistic procedures that are already somewhat aligned with the principles of PBD. Having said this, in recent years researchers have begun to reframe wind engineering procedures with the aim of fully embracing the concepts of PBD [9–16]. However, there still exists a significant amount of work to be carried out if wind engineering is to become a truly PBD-driven discipline.

As mentioned above, the implementation of state-of-the-art PBD requires the use of reliability/probabilistic models for the

---

[*] Corresponding author. Tel.: +1 574 631 2539; fax: +1 574 631 9236.
E-mail addresses: sspence@nd.edu (S.M.J. Spence), kareem@nd.edu (A. Kareem).

http://dx.doi.org/10.1016/j.engstruct.2014.07.026
0141-0296/© 2014 Elsevier Ltd. All rights reserved.

performance evaluation of the system. Compared to traditional deterministic design, this approach therefore entails the use of more complex and computationally cumbersome models. This makes the traditional trial-and-error approach to finding designs that satisfy the multiple performance objectives both time consuming and non-intuitive. This is further compounded if systems that are economically optimum in meeting the performance goals are also desired. To overcome these difficulties PBD procedures must be coupled with optimization algorithms that are capable of rigorously handling the reliability/probabilistic performance assessment models [17]. A class of optimization methodologies that respond to this need are the reliability-based design optimization (RBDO) algorithms [18,19]. Indeed, in RBDO the aim is the resolution of problems that are characterized by generally deterministic cost/objective functions subject to a number of probabilistic constraints (see for example [19] for a review). The recent boom in computational power has spawned intense research in this area (a critical discussion on the latest methodologies can be found in [18,19] as it has opened the door to the possibility of solving problems that were previously deemed intractable. Notwithstanding these research efforts, there is still need for the development of specific RBDO algorithms that efficiently yield optimum solutions to practical probabilistic PBD problems that are often posed in terms of multiple performance constraints, high-dimensional random variable vectors as well as discrete high-dimensional design variable vectors. As succinctly outlined in [19], each of these characteristics makes the RBDO problem non-trivial due to the implicit nature, in terms of the design variable vector, of the probabilistic constraints and the inherently nested nature of the reliability analysis within the optimization loop [19,20].

This paper focuses on defining a probabilistic PBD and optimization framework specifically for wind excited dynamic building systems. In particular, an efficient simulation-based approach is proposed for solving large scale PBD problems that are characterized by uncertain linear systems driven by experimentally determined stochastic wind loads. The approach centers on a novel decoupling procedure that allows problems characterized by hundreds of component-wise reliability constraints and high-dimensional discrete design variable vectors to be solved within a matter of hours on typical desktop workstations.

2. Performance-based design and optimization: problem definition

The implementation of classic PBD is based on the selection of a set of performance objectives that are defined in terms of a number of discrete performance levels [21–24], for example [22–24]: operational (OP); immediate occupancy (IO); life safety (LS); and collapse prevention (CP) that are briefly described in Table 1, and hazard intensities under which they are to be satisfied, for example events with return periods of: 72; 225; 474; and 2475 years respectively [22–24]. For certain special structures other performance levels, such as occupant comfort for tall buildings [10,25], may also need to be considered. In order to assess a given building system against a given set of objectives, the largely deterministic procedures outlined in [21–24] are generally followed. Experience gained from the implementation of this classic approach to PBD has indicated some limitations among which are questions regarding the adequacy of using deterministic, in place of probabilistic, assessment procedures and the need for alternative ways of communicating performance to stakeholders for decision-making purposes [26]. With the aim of defining a new generation of rigorously probabilistic PBD procedures that overcome these and other limitations, researchers at the Pacific Earthquake Engineering Research (PEER) Center have developed what is commonly denominated the PEER framework [3,4]. The aim of this framework is the estimation of the mean rate, generally over an observation period of a year, with which a particular performance metric, such as probable costs of repair and downtime, will exceed various levels for a given design at a given location. Although originally developed for seismic engineering applications, the PEER formula is essentially a re-framing of the reliability integral and is therefore easily applicable to other research areas, such as fire, blast and wind engineering [12,27,28]. In particular, concerning the application of PBD to wind engineering, it is interesting to observe how, in contrast to seismic engineering, the possibility of allowing a wind excited structural system to enter the inelastic range is generally deemed unacceptable. This is most likely due to the difficulty of designing a controlled inelastic response for events of long duration, such as severe wind storms, as well as stakeholders' and society's unease at the idea of structural damage occurring for such a frequently and easily perceived natural hazard. In terms of the classic discrete performance levels, this implies that under severe events the system is generally required to perform at a performance level similar to that described by IO.

Indicating with $\lambda(a)$ the mean rate of exceedance of the event $A = a$ (where capital letters indicate random variables while lower case letters indicate their realizations) and with $G(a|b)$ the complementary cumulative distribution function (CCDF) of random variable A given $B = b$, the PEER framework is expressed as:

$$\lambda(dv) = \int_{dm}\int_{edp}\int_{im} G(dv|dm)\cdot|\mathrm{d}G(dm|edp)|\cdot|\mathrm{d}G(edp|im)|\cdot|\mathrm{d}\lambda(im)| \tag{1}$$

where dv indicates the decision variable corresponding to the performance metric (for example, repair cost); dm is the damage measure indicating the state of damage of structural and/or non-structural parts (e.g. the plastic deformation accumulated in an element, the loss of function of a structural/non-structural element); edp is the engineering demand parameter, which is the value assumed by the structural response parameter that is linked to the damage occurrence (e.g. the rotation of a joint, the inter-story drift); and im is the measure of the intensity of the event (wind, earthquake, etc.). By writing the mean rate as in Eq. (1), the choice has been implicitly made that the parameters dv, dm, edp and im are defined so that dm conditioned on edp is independent of im, and dv conditioned on dm is independent of both edp and im [29]. As such

Table 1
Performance levels and related descriptions.

Performance level	Description	Damage state
Operational	Non-structural components are able to support the pre-earthquake functions present in the building	Very light
Immediate occupancy	Structure substantially retains original strength and stiffness. Damage to nonstructural components, but building access and life safety systems generally remain available and operable	Light
Life safety	Some residual strength and stiffness left in all stories. Potentially significant and costly damage to nonstructural components	Moderate
Collapse prevention	Little residual stiffness and strength, but load-bearing columns and walls function. Extensive damage to nonstructural components	Severe