A performance-based design framework for the integrated collapse and non-collapse assessment of wind excited buildings

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Abstract

Current prescriptive design provisions are moving towards performance-based design approaches in which system-level probabilistic measures are used to explicitly describe performance. While earthquake engineering has embraced these changes over the last few decades, the same cannot be said for wind engineering where design provisions have remained predominantly prescriptive. The significant wind related economic losses incurred each year around the world has spurred strong interest in developing general performance-based wind engineering frameworks. To this end, this paper presents a simulation-based framework for multistory wind excited buildings that rigorously integrates system-level estimates of both collapse and non-collapse losses. In particular, it is proposed to use the theory of dynamic shakedown as an efficient means for describing the collapse probability of the main wind force resisting system. The practicality and potential of the proposed framework is illustrated on a full scale case study.

1. Introduction

The advantages of performance-based design over traditional prescriptive provisions is well known in the field of seismic engineering. In particular, intense research over the past 30 plus years has led to the development of what is commonly referred to as second generation Performance-Based Seismic Design (PBSD) [1,2] and, in particular, the publication by the Federal Emergency Management Agency (FEMA) of the P-58 volumes [3–5]. These documents outline a general methodology that not only accounts for the inevitable uncertainty in accurately predicting the response of building systems subject to severe earthquakes, but also communicates performance through system-level measures that are easily understood by decision-makers and/or stakeholders, e.g. expected repair time and cost. While the framework outlined in the P-58 volumes – and more in general the model proposed by the Pacific Earthquake Engineering Research (PEER) center [1,2] – was developed for buildings subject to earthquake excitation, it is a relatively general procedure that can in theory be extended to other natural hazards such as wind. In this respect, several research efforts have been conducted over the past few years [6–15]. These works have mainly focused on the non-collapse performance assessment of specialized wind excited structures such as tall buildings and long span bridges. However, as outlined in [15], the next steps in applying performance-based design to wind engineering would require the development of general methodologies that can model the behavior of systems subject to a full range of moderate to severe wind events.

To develop such a framework, models that estimate both the non-collapse as well as the collapse performance in terms of probabilistic system-level losses are necessary. Therefore, the possibility of allowing the system to enter an inelastic response regime needs to be taken into consideration in order to avoid leaving the system exposed to undesirable post-yield behavior and possible collapse. In this respect, various contributions have been made towards better understanding how systems respond inelastically to wind [16–24,15]. In particular, the computational challenge of estimating the nonlinear response has been identified as a major issue as, in a nonlinear response regime, the complete duration of the event must be considered if meaningful results are to be obtained. Because of the long duration of typical wind events (in the order of several hours), the possibility of applying robust numerical methods that require direct integration of the nonlinear dynamic equations of motion over the entire duration of the storm, such as incremental dynamic analysis (IDA) [25], are lost. This is especially true if the probability of inelastic response, and ultimately collapse, is desired (which is necessary if frameworks such as the P-58 are to be developed for wind excited systems).
An alternative approach to directly integrating the nonlinear equations of motion, which has recently been applied to the analysis of wind excited systems [26], is that based on applying dynamic shakedown theory [27–32]. These methods have the potential to rapidly provide a complete picture of the post-yield behavior of the structure, indicating, for instance, whether the structure is in shakedown or low cycle fatigue.

In this paper, a simulation-centered Performance-Based Wind Engineering (PBWE) framework for multi-story wind excited buildings is proposed that rigorously integrates both non-collapse as well as collapse performance in terms of system-level metrics such as probable repair costs and downtime. In particular, in estimating the probable repair times, the recent methods outlined in the Resilience-based Earthquake Design Initiative (REDi) guidelines are integrated into the proposed framework, while the theory of probabilistic dynamic shakedown is proposed as a means to fully describe the post-yield behavior of the main wind force resisting system (MWFRS)

2. Performance-based wind engineering: problem setting

The PBWE framework that will be developed in this work will be based on the recently proposed extension to wind engineering of the PEER framework [6,7]. In particular, instead of considering the mean annual rates of exceedance of the thresholds $d_v$, structural performances will here be measured in terms of the annual exceedance probability of the thresholds, $P_f$, as this measure is more commonly used in wind engineering. Thus, performance is assessed by solving the following probabilistic integral:

$$P_f(d_v) = \int \cdots \int G(d_v) \cdot | \frac{dG}{d| \frac{dG}{dp}} | \cdot \left\{ \frac{|dG|}{|dp|} \cdot \left| \frac{dp}{|im|} \right| \cdot \left| \frac{im}{p} \right| \right\} \cdot dim$$

where $G(a/b)$ is the Complementary Cumulative Distribution Function (CCDF) of A conditional on B (where the common convention of using capital letters to indicate random variables and lower case letters for their realizations has been used); $DM$ is the damage measure indicating the state of damage of structural and/or non-structural components; $EDP$ is the engineering demand parameter, i.e. the structural response responsible for causing damage; $IP$ represents a set of interaction parameters (i.e. the aerodynamic loads acting on the structure); and $IM$ is the measure of the intensity of the event with $p/im$ the probability density function of the annual largest values of IM.

As in the case of the FEMA P-58 seismic framework, in this work Eq. (1) is used for estimating the performances of buildings that are repairable, i.e. for buildings that do not collapse during the wind event. To separate collapse from non-collapse, a model based on dynamic shakedown theory will be developed. In particular, since collapse and non-collapse are mutually exclusively events, the probability of the $DV$ exceeding a threshold, $d_v$, considering both scenarios can be expressed through the total probability theorem as:

$$P(DV > d_v) = P(DV > d_v|NC)P(NC) + P(DV > d_v|C)P(C)$$

where $P(C)$ is the probability of collapse, $P(NC)$ the complement of $P(C)$ (i.e. the probability non-collapse), $P(DV > d_v|NC)$ is the annual exceedance probability of $d_v$ given that the building does not collapse, while $P(DV > d_v|C)$ is the annual exceedance probability of $d_v$ given that the building collapses during the event.

In order to solve Eq. (2), models need to be defined for estimating $P(NC), P(DV > d_v|C)$, as well as for the sub-analysis tasks involved in solving Eq. (1). The following sections will outline possible models to this end.

3. The proposed PBWE framework

3.1. Non-collapse assessment

This section focuses on defining appropriate models for carrying out the sub-analyses for solving the non-collapse problem of Eq. (1).

3.1.1. Wind hazard analysis

A common measure of the intensity of an extreme wind event is the maximum wind speed, $v$, to occur at a height of interest $z$ (e.g. building or eave height) averaged over a fixed time interval $T$ (e.g. an hour). As discussed in [13], this parameter is a logical choice for a site specific intensity measure, IM. In particular, IM can be related to meteorological data, $v$, collected at nearby weather stations through a probabilistic transformation, $\Omega$, that accounts for aspects such as differences in the site roughnesses, averaging times, as well as observational and modeling uncertainties [33]. In this work, the transformation outlined in [13] is adopted, which has the following general form:

$$im = \bar{v}_z = \Omega[T, z, z_0, u_{ref}, \tau, (H_{met}, z_{01})]$$

where $\tau$ is the averaging time associated with the meteorological data, $z_0$ and $z_{01}$ are the roughnesses at the site of interest and the meteorological station of height $H_{met}$ respectively, while $U_{ref}$ is a vector collecting the uncertain parameters associated with the transformation of Eq. (3). More details on the transformation of Eq. (3) can be found in [13].

3.1.2. Aerodynamic analysis

After identifying the intensity of the wind event, aerodynamic loads, $F$, acting on the structure need to be determined before the EDPs can be estimated through structural analysis. These loads, defined as the interaction parameters ($IP$), can be obtained from specific wind tunnel tests or associated databases, computational fluid dynamics or quasi-steady models. In general, the interaction parameters will depend on a vector of uncertain model parameters, $U_{ip}$, as well as the intensity of the wind event $\bar{v}_z$:

$$ip = F(t; \bar{v}_z, U_{ip})$$

In this work, a quasi-steady model is used to simulate the wind time histories as outlined in Appendix A.

3.1.3. Structural analysis

The damage models for assessing the system-level building performance developed in this paper are driven by a vector of EDPs defined by structural responses such as displacements $u$, velocities $\dot{u}$ and accelerations $\ddot{u}$. In particular, the EDPs are taken as the maximum responses to occur over the duration, $T$, of the wind event:

$$edp = \max_{0 \leq t \leq T} R(t; F, u_{edp})$$

where $R(t; F, u_{edp})$ is the vector collecting the response processes of interest while $U_{edp}$ is a vector containing the uncertain parameters associated with estimating the structural responses (e.g. the modal damping ratios or Young’s modulus). In particular, the vector $R$ can be formally defined as:

$$R(t; F, u_{edp}) = \Lambda \ddot{u}$$

where $\Lambda$ is an indicator matrix extracting the responses, including combinations (e.g. inter-story drifts), from the augmented response vector $u = [u \; \dot{u} \; \ddot{u}]^T$. In particular, in order to determine the dynamic response of the structure, a modal framework can in general be used [34].

To account for the uncertainties involved in the structural model and material properties, the modal damping ratios, $\xi_i$, and
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