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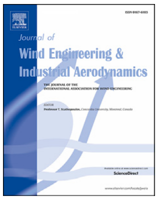

Investigation on life-cycle damage cost of wind-excited tall buildings considering directionality effects

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A R T I C L E I N F O

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A B S T R A C T

Life-cycle cost analysis (LCCA) can be efficiently used to quantify wind-induced damage on a tall building. The LCCA selects an "optimal" design solution by minimizing over structural lifetime the total cost (construction, maintenance and repair). Being based on the *Pacific Earthquake Engineering Research* equation, the LCCA relates the expected cost over the lifetime of the structure to the probability of exceeding specific damage levels. It also accounts for potential sources of uncertainty, such as variability in wind load intensity, directionality, structural properties, damage model estimation, etc. This paper proposes a LCCA methodology that evolves from the approach used in seismic engineering to numerically examine non-structural damage probability and predict maintenance costs on tall buildings by incorporating information on aerodynamic loads measured on a reduced-scale model in wind tunnel. The final objective is to provide an efficient simulation procedure, which simultaneously accounts for stochastic characterization of wind load intensity and direction.

1. Introduction

Wind-exposed tall buildings can experience damage to non-structural components during their lifetime. Non-structural damage can pertain to partition walls, installations, ceilings, façades. For example, damage to façades can be induced by strong winds producing disproportionate lateral interstory drifts, accelerations, large pressures loads at specific locations of the structural envelope or by impact of wind-borne debris. Only in the case of occurrence of very strong wind events like tornadoes, the building can experience structural damage and collapse of structural members (LaFave et al., 2016). As confirmed by forensic engineering investigations after extreme wind hazards, adequate initial design usually avoids altogether such a problem in the case of engineered tall buildings; consequently, most attention is usually devoted to non-structural damage.

In order to assess life-cycle losses in tall buildings due to non-structural damage, an appropriate methodology is required. One such methodology that has gained attention in recent years is the life-cycle cost analysis (LCCA). The LCCA can estimate the total costs of a structure accounting for the effects of uncertainties involved in the design that cannot be neglected (Venanzi et al., 2014, 2015). Moreover the LCCA can account for structural deterioration, structural and non-structural damage, maintenance and repair interventions (Lagaros, 2007; Okasha and Frangopol, 2011). The LCCA is a well established process in earthquake engineering (Aslani and Miranda, 2005; Liu et al., 2004; Mitropoulou et al., 2011; Wen and Kang, 2001) while in wind engineering considerable efforts are still needed to improve applicability of the methods and models.

In Ciampoli et al. (2011) a performance-based design approach for wind engineering is formalized for the first time. In Ciampoli and Petrini (2012), Pozzuoli et al. (2013) the method is employed to assess the risk of exceeding serviceability limit states in tall buildings subjected to wind load. In Spence and Kareem (2014) the research focus is devoted to the definition of site-specific wind hazard models, derivation of suitable fragility functions as well as of consequence functions that can rationally assess damage and monetary losses. Recent works concerning life-cycle cost analysis of structures under wind loads presented relevant contributions in this field by adapting several concepts and methods from the seismic engineering field. Cui and Caracoglia (2015, 2016), Seo and Caracoglia (2013) propose a numerical framework to estimate the life-cycle monetary losses due to wind-induced damage on tall buildings and long-span bridges, respectively. A risk design optimization method for optimizing life-cycle costs and functionality of tall buildings is proposed in Li and Hu (2014). A general framework for the LCCA of tall

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buildings subjected to both seismic and wind excitation is discussed in Venanzi et al. (2017). Minimization of life-cycle cost is also explored for the optimal design of tall buildings under wind load (Huang et al., 2016) and equipped with control devices (Beck et al., 2014; Venanzi, 2015; Wang et al., 2016). In all the methods briefly reviewed above, the monetary loss assessment is based on the numerical estimation of the *Pacific Earthquake Engineering Research* (PEER) equation, which allows computing the probability of exceeding a pre-defined damage threshold and, consequently, *intervention and repair cost* (Ramirez et al., 2012; Ramirez and Miranda, 2012) by accounting for several uncertainty sources in the load and damage model. In a general framework application, the model should first consider the uncertainty related to wind load characterization due to the inherent stochastic nature of the wind load, including both wind speed and direction. Second, it must account for uncertainty in the aerodynamic models and structural properties of the building, which are relevant to the response estimation.

Capitalizing from the existing literature results and recent advancements of models and methods, the main objective of this study is to provide a general and computationally efficient procedure that relates the probability of exceeding a specific non-structural damage state to the intervention and repair cost of a wind-sensitive structure by considering the stochastic nature of the loads. In this first implementation of the procedure, the fundamental sources of uncertainty are considered such as those associated with aerodynamic loads, wind load intensity and directionality. This study makes use of a benchmark building structure, wind tunnel load data and full-scale wind speed and direction data records. By accounting for the probability distribution of the wind direction, the life-cycle cost is evaluated as a function of both time and building's orientation angle. The results of the LCCA procedure provide useful information to the designers and assistance to the selection of the orientation that minimizes the total life-cycle cost. Although the orientation of a tall building in an existing urban context could be significantly constrained by the presence of neighboring buildings, by architectural and functionality issues, the primary role of building orientation in a performance-based design setting has been clearly emphasized by researchers [e.g., Jain et al. (2001)]. Without loss of generality the present paper examines the influence of wind exposure of a specific site on building's design in order to find the best cost-saving structural solution.

The main features and novel features of the proposed procedure are:

1. Contrary to most literature studies concerning LCCA of wind-exposed tall buildings, which assume the intervention and repair cost to be directly associated with the probability of exceeding a pre-selected limit state at a global or floor level, the cost is indirectly related to the probability of exceeding a damage state obtained by incorporating specific structural fragility functions at the component level (e.g., window glass cracking); the damage model is derived for tall, slender, low-frequency structures which are primarily sensitive to dynamic resonant effects, such as interstory drift, rather than direct pressure loads or wind-borne debris (i.e., conceived for a first application example outside of the hurricane-prone regions in the United States);
2. The procedure is computationally efficient since wind tunnel high-frequency force balance (HFFB) records are used and converted to generalized forces along with their uncertainty, enabling the analysis in the frequency domain;
3. Structural damage, intervention and repair costs are separately considered and accumulated along both principal lateral deformation planes of the building;
4. The effect of wind directionality and the building orientation at a specific site are taken into account in the computation of the expected life-cycle costs.

Uncertainty in the wind load estimation is examined and used to assess the probability distributions of the damage-related response components by splitting the wind tunnel records in several segments corresponding to independent realizations of the stochastic load process.

The rest of the paper is organized as follows. The wind damage and loss analysis model is presented in Section 2. The case study is described in Section 3. Section 4 presents the numerical results. Finally, Section 5 examines the effect of the torsional response.

2. Wind damage and analysis model

2.1. Load and response model: motivation and assumptions

The model assumes that, as damage is predominantly non-structural and occurs on secondary structural elements; the main resisting structural system remains linear during the wind event and the response is dominated by the fundamental lateral vibration modes. If the main lateral resisting system is symmetrical and mass eccentricity is small, torsional effects can be neglected in the case of intervention-cost analysis, as suggested by previous studies (Caracoglia, 2014; Cui and Caracoglia, 2015, 2016). This hypothesis is therefore used in the first part of the study, which analyzes the lateral dynamic translation of the building floors only. It is worth noticing that the effect of torsion may possibly affect the life cycle cost results because the consequent horizontal and vertical peak shear strain can act in combination with the translational response of the building, especially for façade elements at the corners, (Charney and Johnson, 1986; Griffis, 1993). These complex aspects should possibly be treated separately as a function of the specific technology of the façade considering the maximum allowable relative movement between the two bonded surfaces of a curtain wall system. Preliminary analysis of torsional response effects is presented in the last part of this study. More detailed investigation will be considered in future developments. The damage analysis is initially conducted in each primary orthogonal lateral deflection planes of the building separately due to the specific benchmark building geometry that was selected; the results along the two directions are subsequently combined to obtain the cumulative effect in both directions. Hence a simplified model is proposed in order to evaluate the influence of the horizontal peak response due to the building torque in combination with the lateral displacement.

2.2. Load and response model: summary description and derivation of principal equations

In this sub-section the fundamental equations of the model are provided for the sake of conciseness as they are derived from a standard frequency-domain approach; the reader is referred to standard approaches used in the wind engineering literature for more details [for example, refer to the description presented in Cui and Caracoglia (2015)]. In order to limit the computational effort required by the LCCA procedure while still preserving adequate estimation accuracy, the wind loads are represented as time-dependent generalized forces and the structural analysis is carried out in the frequency domain (Caracoglia, 2014). The generalized loads of the fundamental lateral modes, associated with the turbulent wind pressure loads on the building's surface, are needed. These quantities can be directly evaluated from wind tunnel data via conventional HFFB tests or can be obtained by integrating synchronous wind pressure measurements.

A key point of the procedure relies on the examination and indirect estimation of wind loading uncertainty by exploiting information derived from the time histories of the experimental pressure loads, measured in wind tunnel by HFFB. In order to examine the measurement uncertainty, a long HFFB record of the total base bending moments is divided in $i = 1, .., N$ segments of equal time duration Δt. Each i^{th} segment is treated as an independent realization of the generalized force which is labeled as $F_{Q_{i,k}}(t)$. The quantity t indicates time ($0 \le t \le T$) and $k = \{x, y\}$ are the principal orthogonal directions of the building. The generalized lateral force $F_{Q_{i,k}}(t)$, from which the structural response is evaluated, can be written as: