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Life-cycle damage-based cost analysis of tall buildings equipped with tuned mass dampers

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ABSTRACT

High-rise buildings are often equipped with Tuned Mass Dampers (TMDs) to reduce wind induced vibrations. Although TMDs are expensive devices, their adoption is justified for improving occupant comfort and avoiding structural damage. Life Cycle Cost Analysis (LCCA) is a valid approach to estimate the total intervention and repair costs of a structure over time. When designing the TMD system for a tall building, the LCCA approach is particularly suitable since final design is a compromise between an increased initial cost and the reduced repair costs because of improved structural performance over the lifetime. Prior work by the Authors proposed an LCCA procedure for quantifying intervention costs on wind-excited high-rise buildings, considering damage to non-structural components. This paper presents an enhanced version of the original method, designated as Life-Cycle Cost Wind Design (LCCWD) procedure, which includes TMD devices. The potential and the efficiency of the approach are examined through numerical investigations.

1. Introduction

1.1. Background and literature review

Tuned Mass Damper (TMD) is the most widespread passive control device for vibration mitigation of tall buildings. It consists of a mass connected to a designated floor of the building through a mechanical apparatus that emulates the behavior of a spring and a dashpot in parallel. If optimally tuned to the natural frequency of the controlled mode, the TMD reduces the building's response. TMD optimization is a topic extensively studied in literature (Den Hartog, 1956). The traditional approach for the TMD design seeks for the minimum TMD mass that guarantees the desired structural performance under random loading such as wind forces (Hoang et al., 2008; Lavan and Daniel, 2013; Warburton, 1982). More recently, uncertainties in the dynamic properties of the structure have been considered for the "robust" optimization of TMDs (Marano et al., 2013; Venanzi, 2015; Venanzi and Materazzi, 2013).

Current design methods identify the most economical control system that satisfies specific performance levels. Indeed, the adoption of TMD control systems is an important initial investment that can lead to intervention cost savings during the structural lifetime because of reduced maintenance and repair. Therefore, the TMD optimization procedure should take into account not only the initial cost but also the projected future savings from a life-cycle perspective.

The Life-Cycle Cost Analysis (LCCA) approach has been recently considered in wind engineering. The LCCA computes, in a probabilistic framework, the total lifetime cost of a specific design solution, accounting for initial costs, repair and maintenance costs, downtime costs and disposal costs. All the uncertainties associated with the problem can potentially be taken into account, such as uncertainty in the wind load characterization, structural and aerodynamic properties, hazard and damage occurrence.

The LCCA is a well established methodology in earthquake engineering (Aslani and Miranda, 2005; Liu et al., 2004; Mitropoulou et al., 2011; Wen and Kang, 2001). The cost assessment is based on the Pacific Earthquake *Engineering Research* (PEER) equation, which allows computing the probability of exceeding pre-defined damage thresholds and, consequently, the corresponding intervention/repair costs by accounting for several uncertainty sources in the load and damage model (Ramirez et al., 2012; Ramirez and Miranda, 2012).

Integral part of the LCCA is the performance-based design, recently introduced in the wind engineering field (Ciampoli et al., 2011). In Ciampoli and Petrini (2012) the method is employed to assess the risk of exceeding serviceability limit states in wind-excited high-rise buildings.

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In Spence and Kareem (2014) site-specific wind hazard models are proposed in conjunction with suitable fragility functions that can rationally assess damage and monetary losses. In Cui and Caracoglia (2015, 2016), Seo and Caracoglia (2013) a numerical framework is developed to estimate the life-cycle monetary losses due to wind-induced damage on long-span bridges and tall buildings, respectively. The framework has been recently extended to study wind-induced damage of a benchmark building in mixed wind climate, i.e. by accounting for both synoptic winds and hurricane events along with their directionality (Cui and Caracoglia, 2017b). A risk design optimization method for optimizing life-cycle costs and functionality of tall buildings is proposed in Li and Hu (2014). A simulation-based framework for multi-storey wind-excited buildings, which rigorously integrates system level estimation of both collapse and non-collapse losses, is proposed in Chuang and Spence (2017). A general framework for the LCCA of tall buildings, subjected to both seismic and wind excitation, is discussed in Venanzi et al. (2017). In Beck et al. (2014) an approach combining statistical linearization with time-variant reliability analysis concepts is used to formulate a life-cycle cost optimization problem and applied to the optimal design of non-linear/hysteretic stochastic dynamical systems.

The LCCA is also a valid tool to evaluate the performance of structural control systems for seismic vibration mitigation. In Matta (2015) a method for evaluating the seismic performance of TMDs in inelastic building structures is presented. In Taflanidis and Beck (2009), a systematic probabilistic framework is presented for the life-cycle cost optimization of engineering systems equipped with viscous dampers under seismic load. In Wang et al. (2016), the life-cycle downtime cost, related to discomfort perception, is explored for the optimal design of tall buildings under wind load and equipped with control devices.

In prior work by the Authors (Ierimonti et al., 2017a,b) the LCCA approach is employed to efficiently quantify wind-induced non-structural damage on a tall building. The procedure is computationally efficient and 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.

1.2. Motivation, novel perspectives and study objectives

Capitalizing from recent developments and studies by the Authors, the main objective of this paper is to propose a generalization and novel implementation of the recently-developed procedure for the design of buildings equipped with TMDs. The enhanced Life-Cycle Cost Wind Design (LCCWD) procedure takes into account the long-term economical consequences and benefits associated with the presence of the TMDs. Contrary to existing literature and previous studies, the procedure is tailored for tall buildings incorporating TMDs to reduce wind load effects. The main improvements of the proposed LCCWD procedure, compared to the existing methods, are related to the modeling of the wind loads, response estimation and the capability of including the effect of the TMD installation in damage probability and cost assessment.

Furthermore, the LCCWD procedure allows for an accurate wind-load characterization. For instance, the uncertainty associated with the aerodynamic load estimation is efficiently taken into account by parsing the experimentally measured generalized wind loads, derived from wind tunnel data; the torsional effects are taken into account; rigorous probabilistic assessment of the wind speed and direction is performed. In particular, the preeminent relevance of wind tunnel errors in the characterization of aerodynamic loads for tall buildings is considered, as recently discussed and examined (Cui and Caracoglia, 2017a).

In the LCCWD, the structural analysis is carried out in the frequency domain and considers power-law function mode shapes and torsional response. Costs related to both drift-sensitive and acceleration-sensitive non-structural components are evaluated. The beneficial contribution of the TMD in reducing both types of damage is assessed from a life-cycle cost perspective. The efficiency of the LCCWD procedure is demonstrated by making use of a tall building structure, for which wind tunnel load data, full-scale wind speed and direction data are available.

The rest of the paper is organized as follows. The LCCA procedure, proposed in Ierimonti et al. (2017b), is reviewed in Section 2. The enhanced LCCWD procedure for structures equipped with TMDs is reported in Section 3. The case study is described in Section 4. Section 5 presents the numerical results and, finally, Section 6 concludes the paper.

2. Background on LCCA for wind-excited tall buildings

The LCCA procedure (Ierimonti et al., 2017b) is a method to assess life-cycle total cost of wind-excited tall buildings. The model assumes that the main resisting structural system remains linear during the wind hazard and non-structural elements are exclusively damaged.

The expected cost evaluation is based on the assumption that the structure is restored to its original condition after each occurrence of the wind-induced damage. The formulation considers maintenance and repair costs but does not account for hazard-independent periodic maintenance and construction costs; the main objective of the LCCA is in fact to compare differences in the wind-damage intervention costs among various design solutions (for example with and without installation of a TMD device). Indirect business losses, associated with activity interruptions, are also not considered at this stage of the work. They could, however, be readily incorporated by “internalization” of the external costs related to business interruptions, as described for example in Seo and Caracoglia (2013) for wind-induced LCCA of long-span bridges.

2.1. Hazard analysis and structural analysis

The structural analysis is carried out in the frequency domain (Caracoglia, 2014) by assuming that the response is dominated by the three fundamental lateral vibration modes (two lateral bending modes and one torsional mode). The modal coordinates are assumed as uncoupled. Three-dimensional mode shapes are not considered in this study but may be readily included without any loss of generality, also considering any inter-modal dependence for modes with closely-spaced frequencies. The response power spectral densities are consequently obtained as:

$$S_{Q_{i,k}}(n) = |H_k(n)|^2 S_{F_{Q_{i,k}}}(n) \tag{1}$$

where $k = \{x, y, \psi\}$ is the index denoting the three principal response components (the displacements of the floor geometric centers in directions x and y and the torsional rotation ψ about the vertical axis z); n is the frequency; $S_{F_{Q_{i,k}}}$ is the power spectral density of the generalized load of the k-th mode with i-th realization; $|H_k(n)|$ is the absolute value of the modal transfer function, defined from:

$$|H_k(n)|^2 = \frac{1}{(2\pi n_{0,k})^4 (M_k)^2 \left[\left(1 - \left(\frac{n}{n_{0,k}}\right)^2\right) + 4\xi^2 \left(\frac{n}{n_{0,k}}\right)^2 \right]} \tag{2}$$

In the previous expression, $n_{0,k}$ is the natural modal frequency and M_k is the k^{th} generalized modal mass $M_k = \int_0^H m(z)\Phi_k^2(z)\mathrm{d}z$, where $m(z)$ is the mass per unit height of the building, H is the building height and $\Phi_k(z)$ is the k-th mode shape. No uncertainty in the physical building properties is assumed in this implementation, whereas variability in the wind loads and their spectrum is considered through index i (Ierimonti et al., 2017a,b).

To characterize the wind forces and compute $S_{F_{Q_{i,k}}}(n)$, the generalized loads of the fundamental lateral and torsional modes, associated with the turbulent wind pressures on the building's surface are evaluated. These quantities can be either directly evaluated from wind tunnel data via conventional high frequency force balance (HFFB) tests or, indirectly, by integrating synchronous wind pressure measurements.