August 27-31, 2023
FLORENCE - ITALY
16th International Conference on Wind Engineering
ICWE 16

Performance-based design optimization of wind-excited structures considering the effects of climate change on the expected life-cycle loss

Thays G. A. Duarte[1], Imad Alhayik[2], Arthriya Subgranon[3]

[1]*University of Florida, Gainesville, United States, tduarte.guerraar@ufl.edu*
[2]*University of Florida, Gainesville, United States, ialhayik@ufl.edu*
[3]*University of Florida, Gainesville, United States, arthriya.subgranon@essie.ufl.edu*

SUMMARY:
This study proposes a performance-based design optimization (PBDO) framework for the minimization of the initial cost of wind-excited systems with a constraint on the expected life-cycle wind-induced loss. In particular, stochastic wind loads considering the effects of climate change on the intensity of wind events are applied to the probabilistic life-cycle performance assessment. To solve the computationally expensive optimization problem, a strategy based on Kriging metamodeling and Auxilary Variable Vectors is proposed in order to approximately decouple the Monte Carlo simulation from the optimization loop. A sequence of approximate optimization sub-problems is solved until the optimal design of two consecutive design cycles converges, ensuring the exact solution to the original problem. The applicability of the proposed framework is demonstrated through the optimal design of a 37-story building where two scenarios are assessed: one considers the climate change effect while the other does not. The results demonstrate the efficiency and effectiveness of the proposed framework as well as shed light on the importance of considering climate change effects for the design of structural systems subject to extreme wind events.

Keywords: performance-based design optimization, non-stationary hazard, life-cycle performance

1. INTRODUCTION

The economic loss and loss of life due to extreme wind events that continue to affect the United States coast have motivated mitigation efforts by improving the performance of structural systems. Among several approaches, the performance-based wind engineering (PBWE) approach has become popular as it enables engineers to design wind-excited structures while explicitly accounting for uncertainties (Ciampoli et al., 2011; Ouyang and Spence, 2020). The integration of optimization methods with PBWE frameworks provides a powerful tool for the identification of optimal systems that are cost-effective while meeting performance requirements.

Even though several PBWE and performance-based design optimization (PBDO) frameworks have been proposed, one aspect that has not been given much attention is the non-stationarity of the hazards and their effects on the design of structural systems (Esmaeili and Barbato, 2022). While stationarity of the hazards is frequently assumed in probabilistic analysis of wind-excited systems, the assumption may not hold true when considering the effect of climate change. Some studies have shown that climate change can affect the frequency, intensity, and location of extreme wind events, hence affecting building responses to such events (Lombardo and Ayyub, 2017). The consideration of climate change effects in the design process within the PBDO frameworks can therefore enhance building resilience over the lifespan and mitigate future losses to wind events.

This study aims at developing a PBDO framework that minimizes the initial costs of wind-excited structural systems while considering a constraint on the expected life-cycle wind-induced loss on the building system. Stochastic wind loads considering the effects of climate change on the intensity of wind events are included. To solve this computationally expensive optimization problem, a decoupling strategy based on Kriging metamodeling and Auxilary Variable Vectors (AVVs) is proposed. The applicability of the proposed framework is demonstrated through the optimal design of a 37-story building where two scenarios are assessed: one considers the climate change effect while the other does not.

2. PROBLEM FORMULATION AND METHODOLOGY

The problem to be solved in this study is to find an optimal design of the wind-excited structural system such that the initial cost is minimized while satisfying a constraint on the expected wind-induced loss over the lifespan of the system. The problem can be expressed mathematically as:

$$\begin{aligned} &\text{Find} && \mathbf{x} = \{x_1, ..., x_N\} \\ &\text{To minimize} && V(\mathbf{x}) \\ &\text{Subject to} && E[L_c(\mathbf{x})] \leq L_0 \\ & && x_n \in \mathbb{R}_n \text{ for } n = 1, ..., N \end{aligned} \tag{1}$$

where $\mathbf{x}$ is the design variable vector (e.g., member cross-section sizes), $V(\mathbf{x})$ is the function associated with the initial cost of the structural system to be designed (e.g., the volume of structural steel), $E[L_c(\mathbf{x})]$ is the function associated with expected life-cycle wind-induced loss, L_c is the life-cycle decision variable (e.g., the repair cost of envelope system over the lifespan), L_0 is the threshold limit of the expected life-cycle loss value, and $\mathbb{R}_n$ is the set of values that each nth design variable can assume.

The life-cycle decision variable may be written as the summation of the decision variable over all events that happen throughout the lifespan as follow:

$$L_c = \Sigma_{k=1}^{K} L_{e,k}(\overline{V}(t), EDP, DM) \tag{2}$$

where K is the total number of extreme wind events that happen during a given lifespan and is modeled as a random variable assumed to come from a homogenous Poisson distribution, $L_{e,k}$ is the decision variable associated with event k (e.g., the repair cost of a given wind event), $\overline{V}(t)$ is the uncertain wind speed and is dependent on the global time scale (e.g., site-specific wind speed at $t = 10$ years after the initial design), EDP is the uncertain engineering demand parameter (e.g. inter-story drift ratio), and DM represents the uncertain damage measure (e.g. cladding fall out).

In order to incorporate the non-stationarity of the hazard over the life-cycle of the building into the proposed PBDO framework, the probabilistic wind speed estimation with climate change considerations established by Lombardo and Ayyub, 2017, is adopted in this study. The approach is based on quantifying the uncertainties related to meteorological data on non-directional wind speed to project extreme wind speed values under different future climatic conditions. First, independent non-directional wind speeds are fitted to a Gumbel distribution using maximum likelihood estimation. This fitted distribution is then used as the baseline distribution of the year $t = 1$ (i.e., the first year of the time frame of interest). The Gumbel distribution function can be described as follows:

$$f(\bar{v}(t)) = \frac{1}{\alpha_\tau(t)} e^{\frac{-(\bar{v}(t)-\mu_\tau)(t)}{\alpha_\tau(t)}} \exp[-e^{\frac{-(\bar{v}(t)-\mu_\tau(t))}{\alpha_\tau(t)}}] \tag{3}$$

where $\mu_\tau(t)$ is the best-fitted location parameter and $\alpha_\tau(t)$ is the best-fitted scale parameter associated with the distribution of year t. From the baseline distribution, two different scenarios are now defined: the present climate (PC) and future climate (FC) scenarios. PC represents no climate change while FC accounts for a change in climate by modifying the best-fitted Gumbel parameters based on the climate change information. To determine FC scenario, a particular range of wind speed values from the baseline Gumbel distribution is modified by a given rate of change. Then, the modified dataset is refitted to the Gumbel distribution to derive a new set of Gumbel parameters (μ_τ, α_τ) associated with the updated t value. This procedure is repeated until the time-dependent wind speed distributions are obtained throughout the building lifespan of interest.

Due to the complexity of the probabilistic assessment of $E[L_c]$, analytical solutions are not usually available and Monte Carlo simulation is the most straightforward approach to solve for such a probabilistic measure. Having the Monte Carlo simulation nested in the optimization loop makes the problem of Eq.(1) become computationally intractable, especially for high-dimensional design and uncertain spaces. To overcome this hurdle, the PBDO framework is proposed here where the decoupling strategy is used to approximately decouple the probabilistic analysis from the optimization loop. In this context, an optimization sub-problem will be defined where $E[L_c]$ is defined as a function of Kriging metamodels and the auxiliary-variable vectors (Suksuwan and Spence, 2019). A series of approximate optimization sub-problems are solved until the optimal design of two consecutive design cycles coincide to ensure the exact solution to the original problem.

3. CASE STUDY AND DISCUSSION

To demonstrate the applicability of the proposed framework, the X-direction lateral load-resisting system of a 37-story building with a 150-m total height is optimized considering both FC and PC scenarios. The building is considered to be located in the Miami area of Florida and has a total of 257 design variables representing beam and column sizes. The initial cost is associated with the structural steel volume, while the life-cycle repair cost is the expected cost to repair damaged cladding components (component B2022.033 on the FEMA Database (FEMA, 2018)), over the 50-year building lifespan. To determine the distribution of the wind speed, milepost 1450 of the hurricane database of the National Institute of Standards and Technology (NIST, 2016) was used, while the climate change effect on wind speed distribution over the lifespan was modeled according to the methodology proposed by Lombardo and Ayyub, 2017.

Figure 1(a) shows the convergence history of the volume of steel for both FC and PC scenarios. The final optimal designs were identified in less than 50 design cycles, which is efficient considering the high-dimensional design space. It is possible to see that by considering the non-stationarity of the hazard, the final volume was about 3% greater than the scenario where no climate change was not considered. Figure 1(b) shows the convergence history of the expected life-cycle cost where the Monte Carlo results and the approximations coincide within the first few cycles, hence showing the effectiveness of the approximation scheme. Additionally, when the optimal building design of the PC scenario was evaluated under the FC scenario, there was an increase of approximately 36% in the expected losses over the building lifespan. These preliminary findings suggest that climate change can have a significant effect on building performance and therefore should be accounted for during the design process.

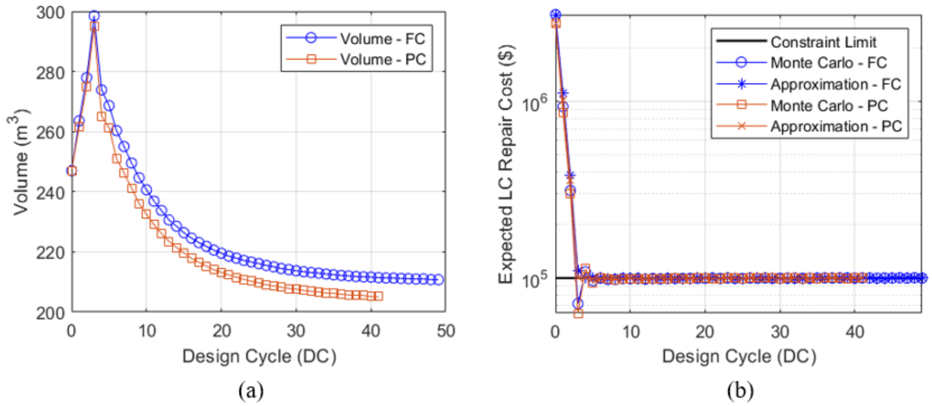

Figure 1. (a) Convergence history of the volume of steel considering FC and PC scenarios, and (b) Convergence history of the expected life-cycle costs for both FC and PC scenarios

REFERENCES

Ciampoli, M., Petrini, F., and Augusti, G., 2011. Performance-based wind engineering: towards a general procedure. Structural Safety 33, 367–378.

Esmaeili, M. and Barbato, M., 2022. Performance-Based Hurricane Engineering under Changing Climate Conditions: General Framework and Performance of Single-Family Houses in the US. Journal of Structural Engineering 148, 04022163.

FEMA, 2018. *P-58-3, Seismic Performance Assessment of Buildings - Supporting Electronic Materials and Background Documentation*.

Lombardo, F. T. and Ayyub, B., 2017. Approach to Estimating Near-Surface Extreme Wind Speeds with Climate Change Considerations. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering 3, A4017001.

NIST, 2016. *Extreme wind speed data sets: hurricane wind speeds*. https://www.itl.nist.gov/div898/winds/hurricane.htm.

Ouyang, Z. and Spence, S. M. J., 2020. A performance-based wind engineering framework for envelope systems of engineered buildings subject to directional wind and rain hazards. Journal of Structural Engineering 146, 04020049.

Suksuwan, A. and Spence, S. M. J., 2019. Performance-based design optimization of uncertain wind excited systems under system-level loss constraints. Structural Safety 80, 13–31.