



Wind Climate-Adaptive Design for Retrofitting Hurricane-Impacted Long-Span Bridges

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SUMMARY

The long-span bridges sensitive to hurricane winds typically play an important role as critical infrastructure components in coastal communities. Hence, the flutter failure probability of these bridges should remain extreme low during their service life. To achieve this goal, various retrofit measures are implemented to mitigate the negative impact of structural deterioration with the assumption of a stationary wind climate. Recent scientific studies suggest that the likelihood of intense hurricanes is increasing from historical values due to emissions of greenhouse gasses caused by human activities; however, the uncertainties in the emission scenarios of future greenhouse gases and in the climate models for future weather extremes pose great challenges to quantify hurricane wind hazard risks under changing climate. To ensure a wide range of future wind climate conditions (with unquantifiable uncertainties) can be accommodated by the retrofitting strategies, an effective retrofitting plan is needed. In this study, three wind climate-adaptive designs are investigated to retrofit hurricane-impacted long-span bridges for the entire remaining lifetime of bridges respectively based on 1) single-horizon one-shot optimization, 2) multi-horizon sequential optimization with a greedy algorithm and 3) multi-horizon sequential optimization with dynamic programming. The simulation results of a case study for retrofitting an existing bridge with non-active appendages installed in a symmetric configuration demonstrate that the dynamic adaptation is beneficial compared to one-shot adaptation considering the increasing uncertainty level with climate projection horizon and advanced sequential decision-making algorithm (i.e., dynamic programming) further increases the benefits.

Keywords: Bridge, Climate Change, Climate Adaptation, Retrofit, Hurricane Winds, Sequential decision making.

1. INTRODUCTION

Recent scientific studies suggest that the likelihood of intense hurricanes is increasing from historical values due to emissions of greenhouse gasses caused by human activities. Since the wind design of long-span bridges along the US East and Gulf Coasts is essentially controlled by hurricane events, it may be necessary to apply appropriate retrofit measures to these existing wind-sensitive coastal bridges that would help mitigate the negative impact of climate change (e.g., lower critical wind speed of flutter instability). To adequately resolve storms in the global climate models (GCMs) for the purpose of obtaining high-fidelity hurricane wind conditions under changing climate, a very fine resolution (e.g., on the order of 1 km or less) with extremely high computational costs is needed (Emanuel et al. 2010). Accordingly, downscaling exercises are typically used to reduce the computational demands of explicitly simulated storms. Ideally, the accurate information about the occurrence probability of emission scenarios, the conditional probability distribution functions (PDF) of regional environmental factors (obtained from GCMs forced by a specific emission scenario) and the conditional PDF of hurricane winds (obtained from downscaling schemes with a given set of environmental factors) is necessary to quantify the hurricane wind hazard risks under changing climate. However, there is no probability assigned to the IPCC (Intergovernmental Panel for Climate Change) future emission scenarios (involving deep uncertainties that are incalculable and uncontrollable). While the low-level uncertainties involved

in the modeling/downscaling techniques can be quantified by using probabilities, there is still significant room to improve the accuracy in the quantification of these uncertainties (e.g., reducing significant biases).

The lack of predictions accuracy for the hurricane winds based on GCMs/downscaling models and the existence of unquantifiable uncertainties in the emission scenarios of future greenhouse gases pose great challenges for stakeholders to make risk-informed decisions on retrofitting planning (PCAST 2023). Hence, it is important to develop a comprehensive decision-making framework for effectively addressing the deep uncertainty complexity (with the hypothesis that climate change is a reality but cannot be projected with a high degree of certainty). To this end, the primary goal of this study is to advance a wind climate-adaptive design to assist stakeholders in making cost-effective retrofitting plans to mitigate climate-change-induced hurricane wind risk to coastal long-span bridges. Specifically, three wind climate-adaptive designs are investigated for retrofitting hurricane-impacted long-span bridges for the entire remaining lifetime of bridges respectively based on 1) single-horizon one-shot optimization, 2) multi-horizon sequential optimization with a greedy algorithm and 3) multi-horizon sequential optimization with dynamic programming. The simulation results of a case study for retrofitting an existing bridge with non-active appendages installed in a symmetric configuration demonstrate that the dynamic adaptation is beneficial compared to one-shot adaptation considering the increasing uncertainty level with climate projection horizon and advanced sequential decision-making algorithm (i.e., dynamic programming) further increases the benefits. While this study only considers the uncertainties of wind demands in the evaluation of flutter failure probability (reliability), the uncertainties involved in other various sources (e.g., bridge performance evaluations) can be straightforwardly integrated into the retrofitting plan.

2. METHODOLOGY

The goal of the retrofitting strategy is to achieve a desired level of flutter performance (target reliability) at a minimum cost. Accordingly, the cost of the retrofitting intervention must be minimized and the aeroelastic performance, i.e., the critical flutter velocity, must be higher than a predefined threshold (compared to the design wind speed under changing climate) to achieve the target reliability and therefore must be treated as a design constraint.

2.1. Hurricane wind risk assessment under changing climate

To accurately assess the hurricane wind hazard risk under changing climate, the occurrence probability of climate change emission scenario, conditional probability distribution functions (PDF) of regional environmental factors [given a climate change scenario (considering inherent uncertainties and climate model differences)] and conditional PDF of hurricane wind hazard (given a set of environmental factors) should be carefully examined. Although IPCC does not assign probabilities to its future emission scenarios, increasing researches have suggested that a likelihood should be given to each IPCC representative emission scenario for better inform climate adaptation policy (Dessai and Hulme 2004). These prescribed probabilities of emission scenarios will be propagated to PDF of environmental factors through multiple GCMs. To reduce the computational costs of explicitly simulated storms (and associated boundary-layer wind field), downscaling exercises are typically used. There have been efforts in the engineering community to conveniently and efficiently consider the influence of the warming climate on hurricane activities by integrating the projected environmental conditions into a hurricane risk assessment framework, generally

involving a hurricane track model (consisting of genesis, trajectory, and intensity modeling components) to generate the synthesized storms. The assessment of hurricane surface wind hazard under changing climate can be achieved by coupling a hurricane track and hazard models.

In this study, the target is to generate wind speed distribution under the requirements of climate adaptation considering the uncertainty from different GCMs. Ten GCMs are applied in this study to provide the environmental variables, and the climate-dependent stochastic simulation framework of hurricane wind hazard developed at University at Buffalo is employed to for hurricane track and wind field generation (Snaiki and Wu 2020). The New York City (NYC) is selected as the studied site (40.71427N, 74.00597W).

2.2. Flutter performance evaluation of a deck-winglet system

This investigation addresses the wind-climate adaptation of long-span bridges adopting an aerodynamic passive countermeasure that increases the aeroelastic performance of bridges. As a representative case of aerodynamic retrofitting, the addition of passive winglets in symmetric configuration to existing bridges to increase the critical flutter velocity is considered here. Figure 1 sketches the resulting deck-winglet system. The winglets contribute by changing the fluid-structure interaction parameters, namely the flutter derivatives, of the retrofitted deck to improve the deck aeroelastic stability. The design variables for the retrofitting system are the winglet size, position, and angle of attack. Assuming that there is enough separation between the deck and the winglets so that the flows around them are not disturbed between them and that the winglet is moving at an oscillatory motion at the same frequency of the deck, the total aeroelastic load on the deck-winglet system is given by:

$$L = L_d + L_w \quad (1a)$$

$$M = M_d + M_w - rBL_w \quad (2b)$$

where L and M are the lift and moment loads on the deck-winglet system, L_d and M_d are the loads and the deck, and L_w and M_w are the contributions of each winglet. Based on Eq (1), the flutter derivatives of the bridge-winglet system can be estimated following the equations in Cobo del Arco (1998). Accordingly, the critical flutter velocity can be efficiently obtained with the closed-form solution developed by Frandsen (1966).

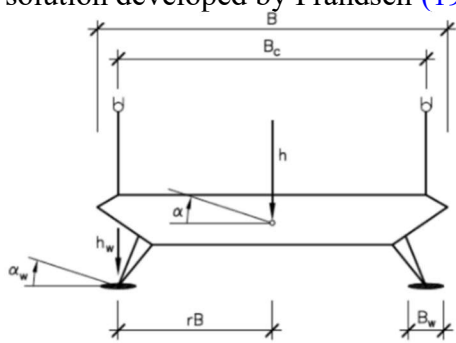


Figure 1: Bridge deck retrofitted with two winglets in symmetric configuration.

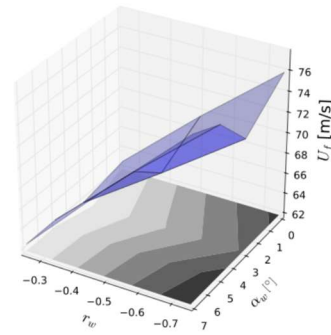


Figure 2: Flutter velocity response surface of the deck-winglet system.

2.3. Wind climate-adaptive design for retrofit measures

Three retrofitting strategies considering flutter reliability conditions are comprehensively evaluated and compared, including (1) a “one-shot” retrofit measure obtained by traditional optimization for the entire time horizon (e.g., remaining lifetime of bridges), (2) a “sequential”

retrofit measures obtained by independently solving a number of optimization problems (with a greedy algorithm) for a prescribed time interval (e.g., every 10 years) within the time horizon, and (3) a “sequential” retrofit measure obtained by dynamic programming for the same time interval.

3. CASE STUDY

A structural system consisting of a 1-node 2-DoF deck supporting system is used as a case study. The mechanical properties adopted are summarized as: bridge width $B = 31$, bridge lightness parameter $\mu = 24.10$, bridge mass distribution parameter $\gamma = 0.67$, bridge vertical frequency $\omega_h = 0.10$ and bridge torsional frequency $\omega_\alpha = 0.25$, while the deck cross-section aerodynamic properties of the Great Belt Bridge. The flutter velocity of the bridge deck without winglets is $U_{f,d}=63$ m/s. Figure 3 shows the flutter critical velocity response surface as a function of the position and attack angle of winglet (with $B_w = 1.55$ m) in a symmetric configuration. It can be seen how the flutter velocity can be increased up to 14 m/s, even with a relatively small winglet. The winglet position r_w , along with the winglet size B_w , are the most influential design variables as they can effectively improve the bridge flutter performance at the expense of retrofitting cost.

Three retrofitting strategies are applied to this case study bridge with the objective function to minimize is the cost of the retrofitting action, which is a function of the design variables and defined as the sum of costs at all time steps:

$$F(\mathbf{r}_w, \mathbf{B}_w) = \sum_{t=1}^T C_t^{intervention} + C_t^{materials} + C_t^{maintenance} \quad (2)$$

where $C_t^{intervention}$ represents the cost of conducting a retrofitting action, $C_t^{materials}$ means the cost of actual construction from retrofitting action, and $C_t^{maintenance}$ is the maintenance cost.

4. CONCLUDING REMARKS

The simulation results of a case study for retrofitting an existing bridge with non-active appendages installed in a symmetric configuration demonstrate that the dynamic adaptation is beneficial compared to one-shot adaptation considering the increasing uncertainty level with climate projection horizon and advanced sequential decision-making algorithm (i.e., dynamic programming) further increases the benefits.

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REFERENCES

- Cobo del Arco, D., 1998. An analysis of wind stability. Improvements to the response of suspension bridges. Doctoral dissertation, Polytechnic University of Cataluña.
- Dessai, S. and Hulme, M., 2004. Does climate adaptation policy need probabilities?. *Climate policy*, 4(2), 107-128.
- Emanuel, K., Oouchi, K., Satoh, M., Tomita, H. and Yamada, Y., 2010. Comparison of explicitly simulated and downscaled tropical cyclone activity in a high-resolution global climate model. *Journal of Advances in Modeling Earth Systems*, 2(4).
- Frandsen, A.G., 1966. Wind Stability of Suspension Bridges. Application of the Theory of Thin Airfoils. In: *International Symposium on Suspension Bridges*, Laboratorio Nacional de Engenharia Civil, Lisbon.
- PCAST (President’s Council of Advisors on Science and Technology), 2023. *Extreme Weather Risk in a Changing Climate: Enhancing Prediction and Protecting Communities*. Executive Office of The President, Washington, D.C., USA.
- Snaiki, R. and Wu, T., 2020. Revisiting hurricane track model for wind risk assessment. *Structural Safety*, 87, 102003.