Structural Fragility Analysis of Tall Buildings and Towers via Artificial Neural Network Surrogate Modeling

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ABSTRACT: Although the standard Monte-Carlo simulation has been widely used in today’s PBWE framework due to its robustness and convenience, it is rather time-consuming and computationally expensive. Drawing motivation from a challenge encountered by the wind engineering community, this study proposes a novel simulation approach, based on surrogate modeling, to computationally analyze structures under wind loads more efficiently compared to both Model-Monte Carlo and other simulation methods (e.g., Stochastic Approximation), examined by the Authors. Artificial Neural Networks (ANN) are proposed and investigated in this study to generate a “surrogate model”. Numerical results indicate that ANN-based models are efficient for stochastic structural analysis of tall buildings and towers with acceptable prediction errors. Particular consideration will be devoted to the study of wind loads and response in mixed wind climates, characterized by the presence of both tropical hurricanes and extra-tropical depressions.

Keywords: high-rise buildings, hurricane simulation, fluid-structure interaction, surrogate models, artificial neural networks

1. INTRODUCTION

Performance-based wind engineering (PBWE) has emerged as an active research field due to potential applications into design standards e.g., by the American Society of Civil Engineers in the United States of America (ASCE, 2019). Novel and accurate methodologies are needed to implement practice-oriented guidelines. This study will examine the use of surrogate models, utilizing the paradigm of artificial neural networks (ANN) in Machine Learning to conduct wind-induced structural dynamic analysis. Fluid-structure interaction and dynamic effects will be examined. Both serviceability and ultimate limit states will be considered in the context of PBWE. Application to vertical tower and building structures is envisioned. Multi-layer ANNs will be employed as surrogate models to reproduce fragility curves and surfaces, as a function of both mean wind speed and direction, examining various relevant limit states (e.g. non-structural damages on the façade, acceleration discomfort levels for occupants, demand-to-capacity indices of selected structural elements).

The study utilizes a recently developed surrogate model and method, designated as Layered Stochastic-Approximation Monte-Carlo (LSAMC; Giaccu and Caracoglia, 2018) to compare the results, found by ANN-based models, assessing the performance of a standard tall building and a monopole tower structure against turbulent wind loads. Furthermore, standard Monte-Carlo sampling simulations will be considered as well to assess adequacy of ANN-based surrogate models.

2. MODEL AND METHODS

The ANN-based, surrogate model is based on a typical ANN topology, formed by combining ANN neurons and organizing them in an input layer (input random variables), hidden layer(s), and an output layer. The variables of the input layer are generally user-defined, e.g. aerodynamic force coefficients, vortex shedding and wake excitation properties, structural properties and other
physical quantities. The hidden layers are the result of calculations from the input layer. Finally, the output layer is the result of the calculations. In an ANN, each node in each layer is connected to each node in the adjacent layer. An ANN will be employed to predict selected probabilities of failure associated with specified limit states of two structural examples, i.e. “fragility” conditional on mean wind speed and direction. Predictions follow a training process, which is carried out using an existing set of input–output data (“supervised learning”). The training of an ANN is commonly performed through a back-propagation algorithm and a minimization process that has three steps.

Similar to the idea of the Latin Hypercube sampling, the LSAMC method uses a layered sampling of the random variables within a Monte-Carlo simulation environment. The key steps of the LSAMC method include: (i) dividing the range of each random variable into a finite number of adjacent, non-overlapping equally-probable intervals; (ii) constructing a subspace of the random variables for each iteration, consisting of one of the equally-probable intervals for every random variable; (iii) feeding the subspace to the standard Stochastic Approximation (SA) algorithm (Spall, 2005), to find one root of the examined problem subjected to random wind load perturbation. Thus, iterating through all the possible subspaces of the original random variable set yields a sequence of roots to the perturbed problem, which are employed to evaluate the effects of the perturbation noises in a structural system through statistical moments, derived from the root sequence.

3. PRELIMINARY RESULTS
In this preliminary study, the only source of uncertainty considered is the static flow forces (drag coefficient of the load, $C_D$). A number of scenarios are designed to examine wind-induced damage through violation of a serviceability limit state (e.g., the rooftop lateral drift and acceleration) and an ultimate limit state (e.g., the yielding of a steel corner-column). One of these scenarios, considering drag flow forces as an independent random input, is presented in detail.

Figure 1. Fragility against the peak lateral rooftop drift of the CAARC standard building with random parameter $C_D$, comparisons between the brute-force Monte-Carlo simulations (BF) and LSAMC method results.

Figure 1 illustrates an example of fragility analysis and examines the peak lateral drift of the CAARC standard building as a function of mean wind speed $\bar{U}(h)$, referenced at rooftop $h =$
183 m, and mean-wind direction $\Psi$. The details of other scenarios and results exploiting ANN-based surrogate models will be described in the final presentation.

4. DISCUSSION AND CONCLUSIONS
Surrogate models, in particular those exploiting the latest developments in the field of Artificial Intelligence, have been explored to replace the standard Monte-Carlo method, and later developments, such as the LSAMC method. Various scenarios have been studied to predict selected structural “failure” probabilities. Numerical results suggest that ANN-based methods can provide efficient and robust approximation of fragility, and can be employed for life-cycle cost analysis of wind-induced damage on tall buildings and towers in turbulent, synoptic wind environments.

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REFERENCES
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