Time Variant Hurricane Modeling in Performance-based Wind Engineering

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ABSTRACT:
Over the past decades, significant research effort has been put into the development of frameworks for the performance assessment of engineered buildings in wind engineering. However, there is still a significant lack of frameworks for the envelope systems of this class of buildings. In order to address this issue, this paper proposes a performance-based assessment framework based on full hurricanes, where probabilistically continuous wind speed, wind direction, and rainfall intensity are captured with random event durations through a set of computational models. An innovative non-stationary/-straight/-Gaussian wind pressure model is introduced to model the full hurricane induced pressure. To illustrate the framework, 45 story archetype building in downtown, Miami, FL, is studied. A full range of probabilistic performance metrics in terms of the amount of damages, losses, and water ingress are evaluated and compared with the same metrics estimated for nominal hurricanes.

Keywords: Performance-based Wind Engineering, Envelope Systems, Wind Driven Rain, Hurricane Modelling.

1. INTRODUCTION

Performance-based wind engineering (PBWE) is becoming accepted as a rational way to assess risks associated with building systems subject to extreme winds. Even though multiple frameworks have been developed for the performance assessment of structural systems of engineered buildings and the envelope systems of low-rise buildings, limited frameworks exist for evaluating the envelope performance of engineered buildings. While the methodology outlined in (Ouyang and Spence, 2020) does explicitly focus on the performance evaluation of the envelope system, it is based on a classic nominal representation of the wind hazard, in which hurricanes are simulated as 1-hour events with constant mean wind speed, wind direction, and rainfall intensity. However, hurricanes will in general have various event durations as well as continuously varying wind speed, wind direction, and rainfall intensities. The adequacy of the adoption of a nominal representation of hurricanes in estimating the envelope system performance has not been studied. To fill this gap, synthetic hurricane-based hazard analysis is suggested in this work, where the envelope and structural system response are evaluated through hurricanes with full evolutions of wind speed, wind direction and rainfall intensity.

The characteristics of full hurricanes necessitate a new set of models to simulate the non-stationary/-straight/-Gaussian wind pressure processes and the transient wind-driven rain intensity field. Herein, an innovative wind-tunnel informed proper orthogonal decomposition (POD)-based nonstationary simulation framework with a non-Gaussian translation model is introduced to simulate the full hurricane induced wind pressures. To enable efficient simulation of the evolution of wind-driven rain, a CFD-based interpolation-enabled simulation strategy is proposed.

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2. PERFORMANCE-BASED WIND ENGINEERING SETTING

The evaluation of envelope system performance consists of the three analysis steps of: hazard analysis; system analysis; and loss analysis. In the hazard analysis, uncertainties in the hurricane hazard climate are modelled through a set of parametric models of the hurricane track, wind field, and filling rate (Vickery and Twisdale, 1995b). In the system analysis, the aerodynamic response of the system is modelled through a non-stationary/-straight/-Gaussian wind pressure model that is calibrated to classic wind tunnel data and ensures efficiency through the use of spectral proper orthogonal decomposition. System measures associated with damages are evaluated for each envelop component considering both structural and net pressure demands through adopting the progressive damage model recently introduced in (Ouyang and Spence, 2020). In the loss analysis, approaches based in consequence functions are used to translate damages into losses. Through a conditional stochastic simulation framework, general model and load uncertainties are propagated to the system responses therefore enabling the estimation of probabilistic performance metrics related to total loss (e.g. monetary loss or downtime) and the total amount of water ingress. Mathematically, the proposed hurricane framework can be expressed through the following integral:

$$\lambda(dv) = \iiint G(dv|sm)|G(sm|\Theta)||G(\Theta|\bar{v}_H)||d\lambda(\bar{v}_H)| \quad (1)$$

where $\bar{v}_H$ is the maximum hourly-mean wind speed measured at the building top, Θ is a vector collecting the hurricane model parameters, sm is the vector of system measure variables (e.g. the number of damaged components and the volume of water ingress), and dv is the decision variable of interest to the stakeholders, e.g. repair costs.

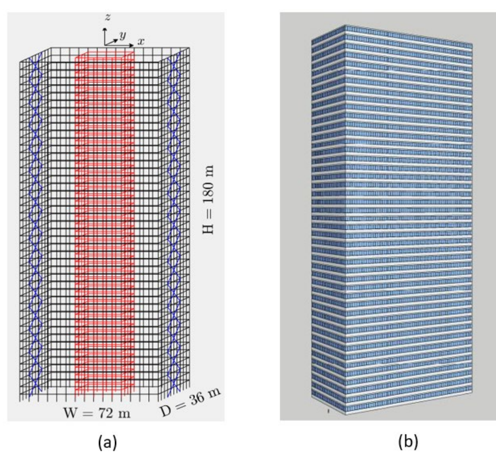

Figure 1. The building archetype: (a) a 3-D view of structural system (b) cladding system layout

4. CASE STUDY

The building archetype defined in (Ouyang and Spence, 2020), and shown in Fig. 1, was considered for illustrating the framework. This building consists of a 45 story steel structure with 8100 dual pane laminated glass units defining the envelope. The glass units are considered as the only damageable components, which are modelled through fragility functions associated with two drift induced damage states $DS_{D_r,1}$ and $DS_{D_r,2}$ and one pressure induced damage state $DS_{P_{60}}$. The hurricane hazard environment at the building site was calibrated through the HURDAT database reported by Vickery and Twisdale (1995b). In calibrating the non-stationary/-straight/-Gaussian wind pressure, building specific wind tunnel data is used. Subset simulation is implemented to estimate the hazard curve through a set of sub-events. The sub-events samples are subsequently used in the stochastic simulation algorithm proposed by Ouyang and Spence (2020) to evaluate the probabilistic envelope performance of the case study structure. The resulting performance metrics, in terms of the total number of damaged components, total repair cost, and total volume of water ingress, are reported in Table 1.

Table 1. System measure and decision variables for different mean recurrence intervals (MRI).

Performance metrics	MRI = 500	MRI = 1000	MRI = 10^4	MRI = 10^5	MRI = 10^6
Number of components in $DS_{Dr,1}$	0	3	29	137	177
Number of components in $DS_{Dr,2}$	0	4	33	138	216
Number of components in DS_{P60}	1	55	215	409	651
Total loss [million US dollars]	0.0041	0.13	0.81	2.24	3.0
Total loss* [million US dollars]	0.0047	0.063	0.48	1.5	3.8
Total volume of water ingress [m^3]	3	270	2800	5300	5800
Total volume of water ingress* [m^3]	0.3	230	200	700	1200

* Nominal hurricane results

The results of Table 1 show that the pressure induced damages have dominated over the drift induced damages. The total losses estimated through adopting a nominal hurricane setting are underestimated, as compared to a full hurricane setting, for nearly all MRIs. In particular, underestimations of up to 52% are seen. The total volume of water ingress estimated by nominal hurricanes is underestimated for all MRIs with maximum underestimations exceeding 90%. These results illustrate the importance of considering a full hurricane representation during the application of PBWE.

5. CONCLUSIONS

In this paper a performance-based wind engineering framework for building envelope systems subject to full hurricanes was introduced. Through a conditional stochastic simulation approach, the framework is capable of evaluating the probabilistic metrics associated with envelope system of engineered buildings under full hurricanes. A case study of a 45 story archetype building has shown that the damages and losses estimated by nominal hurricanes will in general be underestimated for mean recurrence intervals of less than 10^6 years while estimates of water ingress will be underestimated by up to an order of magnitude.

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