CWE-8
June 7-11, 2026
London, ON, Canada

Numerical simulations of hurricane wind loading in the presence of waves

Max Beeman[a], Hanul Hwang[b], Jianyu Wang[c], Catherine Gorlé[d]

[a]Stanford University, Stanford, CA, USA, mbeeman@stanford.edu
[b]Stanford University, Stanford, CA, USA, hanul@stanford.edu
[c]Stanford University, Stanford, CA, USA, jywang96@stanford.edu
[d]Stanford University, Stanford, CA, USA, gorle@stanford.edu

Summary

When modeling wind loads on coastal buildings, approaching tropical cyclone (TC) wind is typically conditioned over regularly spaced roughness elements in both numerical simulation and physical experiments. This conditioning does not accurately represent the complex environment that occurs during TCs when wind, waves, and storm surge occur simultaneously. In this work we will compare a two-way coupled modeling approach (a two-phase phase-field method) to a one-way coupled modeling approach (such as an immersed boundary method) to evaluate how each approach captures the incoming wind profile and loading on a sample house structure. We make this comparison under both old wave and young wave conditions.

Keywords: *wind-wave interaction, hurricanes, large eddy simulation, immersed boundary methods, two-phase simulations*

1 INTRODUCTION

When modeling wind loads on coastal buildings, tropical cyclone (TC) wind flow approaching structures is typically conditioned over regularly spaced roughness elements in both numerical simulation and physical experiments, but this does not accurately represent the complex environment that occurs during TCs when wind, waves, and storm surge occur simultaneously. Regimes of wind-wave interaction are typically described using the non-dimensional parameter wave age, defined as wave phase speed over friction velocity $\left(\frac{c_p}{u^*}\right)$ or 10-m height wind speed $\left(\frac{c_p}{u_{10}}\right)$. When wave age is small, the waves are considered ‘young’ and significant energy transfer from the wind to the waves is expected. The opposite is expected for large wave age or ‘old’ waves. During hurricanes, wave swells are well-developed and steep but the wind speed is so high that the waves are still generally in the young wave regime. Under these conditions, phenomena such as flow separation over wave crests and injection of turbulence into the air phase due to wave breaking are expected to occur. The interactions of these different flow physics could substantially alter expected wind loading on coastal structures. The aim of this work is to investigate the suitability of various numerical approaches for modeling hurricane wind loading in the presence of waves.

Two-phase flow simulations, which incorporate two-way coupling between air and water, provide an opportunity to simulate fully coupled wind and wave loading on coastal structures. However, the ability of these methods to accurately represent interface stresses in young wave age conditions has not yet been well validated. Furthermore, it is not clear that the complexity of these simulations is necessary to accurately capture wind-wave interaction at high wind speeds, as it has been observed in existing wind-wave literature that wind flow patterns over idealized water-waves in the young wave age regime are qualitatively similar to flow over stationary bumps or surface roughness (Sullivan 2000). In this work we will compare a two-way coupled modeling approach to a one-way coupled modeling approach under both old wave and young wave conditions to evaluate how each approach captures the incoming wind profile and loading on a sample building.

2 METHODS

Large eddy simulations (LES) are performed using the CharLES low-Mach CFD solver developed by Cascade. The solver uses an unstructured, Voronoi mesh, with second-order central difference discretization in space and a second-order backward difference scheme in time (Ambo 2020). The LES subgrid-scale model is the Vreman model.

In the current work, we first establish a baseline for comparison by simulating turbulent wind flow over a stationary solid wall (SW) bottom surface and examine the resulting loading on a sample structure. Next, we compare this result to flow over a stationary surface simulated using a mid-fidelity IBM. Then, we simulate flow over an IBM surface moving according to the expected Lagrangian particle trajectories of water waves. Finally, we compare these results to those of simulations performed in a two-phase numerical framework. A schematic of the proposed set of simulations is shown in Figure 1. The remainder of this section will detail the specific IBM and two-phase methods in use, followed by an overview of the wind, wave, and geometry set-up.

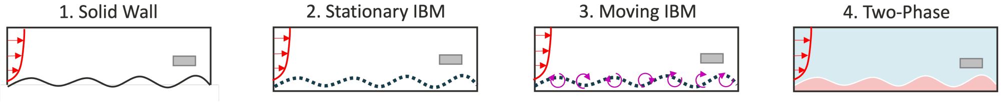

Figure 1: A schematic of the proposed set of simulations. The solid wall, stationary IBM, and moving IBM are one-way coupled, whereas the two-phase simulations capture two-way coupling between air and water.

Immersed boundary methods (IBMs) can be used to impose a wave surface as a bottom boundary condition in a wind-only simulation. Unlike body-fitted meshing, IBMs do not require expensive remeshing to allow surface movement. A wide range of methods with differing fidelity and model complexity have been developed in IBM literature. Since we are interested in the effects of the wave surface on the incoming wind profile and pressure loading on the building, and not in the flow statistics directly on the surface, the extent to which the fidelity of the water surface representation affects the relevant quantities of interest remains an open question. While the current simulations use a mid-fidelity IBM approach of Uhlmann (2005), we hypothesize that a lower-fidelity IBM would also be able to appropriately capture the relevant quantities of interest. One such example of a low-fidelity IBM is the Immersed Body Force Method (IBFM) approach of Muñoz-Esparza et. al. (2020), based on Chan & Leach (2007).

The two-way coupled modeling approach used in the current work is a phase-field approach called Accurate Conservative Diffuse Interface (ACDI) method developed by Hwang & Jain 2022. In this method, the volume fraction of the water phase is tracked in each cell using the phase-field variable, ϕ. The interface advection equation includes an interface regularization term that is derived from thermodynamic principles and includes both diffusive and sharpening components, which serve to maintain a regular interface thickness over a small number of cells at the interface.

The structure is a single-story elevated building, similar in size to the full-scale elevated buildings modeled at facility-scale in the experiments of Abdelfatah et al. (2022). Prior literature has identified that stilts significantly alter local loading in their immediate vicinity, so to isolate the effects of waves, we simulate a 'hovering' building that sits elevated above the water surface without the inclusion of stilts in the simulation geometry. Initial results presented here are performed on a coarse mesh with a cell size of 25cm on the wave and 12.5cm on the building. Next steps include a resolution sensitivity study.

For initial comparison, a log-law mean streamwise velocity profile of 5 m/s at 10m above the water level with $z_0 = 10^{-3}$ m is imposed at the inlet without any turbulent statistics, such that any turbulence that develops is a result of the bottom boundary. Future simulations will incorporate appropriate turbulence generation at the inlet. The stationary regular wave surface imposed is an Airy wave with a wave height of $H = 1.2$m, period $T = 5$s, wavelength $\lambda = 36.6$m, steepness $ak = 0.1$, and depth $d = 10$m (deep water). Ten wavelengths are included in the domain upstream of the structure. The initial results are for a stationary wave with $c_p = 0$ m/s, but in the moving and two-phase simulations, the same wave size and wind speed would result in an old wave age of $c_p/u_{10} = 1.46$.

3 INITIAL RESULTS

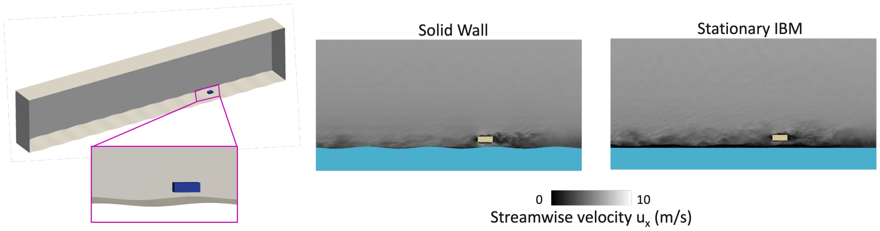

Figure 2: (Left) Domain and 'hovering' elevated building geometry. (Middle & Right) Snapshots at 130s of streamwise velocity for the solid wall and stationary IBM old wave, coarsest mesh simulations.

Initial results include a comparison between the solid wall and stationary IBM simulations at old wave age for the coarsest mesh resolution. A snapshot at $t = 130$s of the streamwise velocity for each of these simulations is depicted in Figure 2. In addition, Figure 3 illustrates vertical profiles of streamwise turbulent intensity at five locations upstream of the building, time averaged over 50s of simulation time for both the solid wall and stationary IBM simulations. In both Figure 2 and Figure 3, it is evident that the stationary IBM representation of the wavy surface has injected more turbulence into the air than the solid wall. Figure 3 shows the percent difference of the stationary IBM streamwise turbulent intensity from the solid wall result for locations upstream of the building at the roof height and at underside height. For some locations, the stationary IBM approach matches the solid wall within 10%, even at this coarsest mesh resolution. While this result is promising, other locations see deviations of more than 50%. There appears to be a correlation between the discrepancy and the wave phase, indicating a need to better understand this comparison.

4 CONCLUSION & FUTURE WORK

Initial comparisons between solid wall and stationary IBM show promise, but challenges remain. Immediate next steps include investigating a lower-fidelity immersed boundary approach and performing model parameter sensitivity studies. Ensuing work includes incorporating movement into the IBM, performing the two-phase simulations, and repeating all simulations at a young wave age.

Further analysis will include detailed examination of how the presence of waves influences upstream flow development. In addition, we will compare pressure contour maps on the surfaces of the elevated building between the different waves representations to determine if there exist discrepancies between the observed loading in these simulations and the expected behavior as

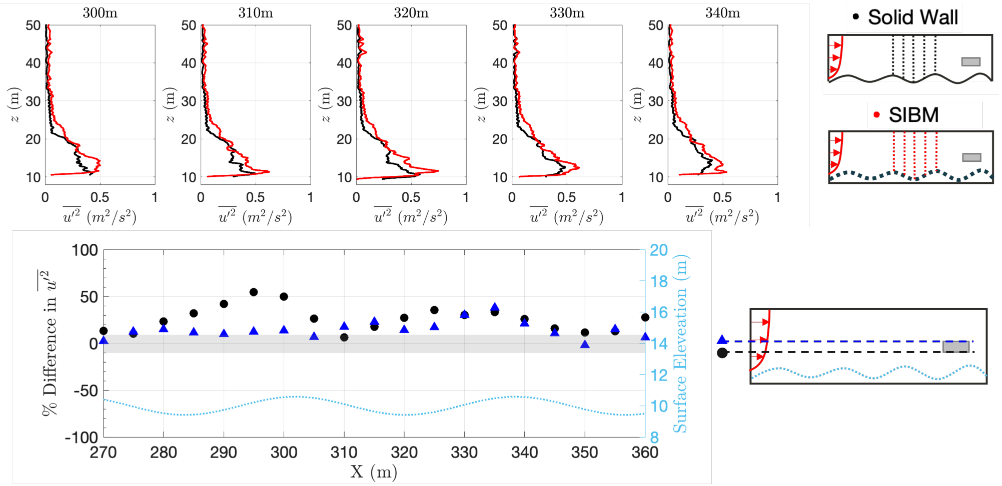

Figure 3: Top: Vertical profiles of streamwise turbulent intensity compared between the solid wall and stationary IBM simulations. Bottom: Percent difference of the stationary IBM streamwise turbulent intensity from the solid wall result at roof height (blue triangles) and at underside height (black circles).

specified by the ASCE-7 building code underside surface zones.

ACKNOWLEDGEMENTS

We gratefully acknowledge computing resources provided by the Stanford Research Computing Center in addition to funding support from the Stanford Gabilan Graduate Fellowship and NSF Graduate Research Fellowship Program.

REFERENCES

Abdelfatah, N., Elawady, A., Irwin, P., & Gan Chowdhury, A. (2022). Experimental investigation of wind impact on low-rise elevated residences. Engineering Structures, 257, 114096. https://doi.org/10.1016/j.engstruct.2022.114096

Ambo, K., Nagaoka, H., Philips, D. A., Ivey, C., Brès, G. A., & Bose, S. T. (2020). Aerodynamic force prediction of the laminar to turbulent flow transition around the front bumper of the vehicle using Dynamic-slip wall model LES. In AIAA Scitech 2020 Forum. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2020-0036

Chan, S. T., & Leach, M. J. (2007). A Validation of FEM3MP with Joint Urban 2003 Data. https://doi.org/10.1175/2006JAMC1321.1

Hwang, H., & Jain, S. S. (2024). A robust phase-field method for two-phase flows on unstructured grids. Journal of Computational Physics, 507, 112972. https://doi.org/10.1016/j.jcp.2024.112972

Muñoz-Esparza, D., Sauer, J. A., Shin, H. H., Sharman, R., Kosović, B., Meech, S., García-Sánchez, C., Steiner, M., Knievel, J., Pinto, J., & Swerdlin, S. (2020). Inclusion of Building-Resolving Capabilities Into the FastEddy® GPU-LES Model Using an Immersed Body Force Method. Journal of Advances in Modeling Earth Systems, 12(11), e2020MS002141. https://doi.org/10.1029/2020MS002141

Sullivan, P. P., McWilliams, J. C., & Moeng, C.-H. (2000). Simulation of turbulent flow over idealized water waves. Journal of Fluid Mechanics, 404, 47–85. https://doi.org/10.1017/S0022112099006965

Uhlmann, M. (2005). An immersed boundary method with direct forcing for the simulation of particulate flows. Journal of Computational Physics, 209(2), 448–476. https://doi.org/10.1016/j.jcp.2005.03.017